



Precise starshade stationkeeping and pointing with a Zernike wavefront sensor

Michael Bottom
High contrast imaging (383A)
Jet Propulsion Lab,
California Institute of Technology

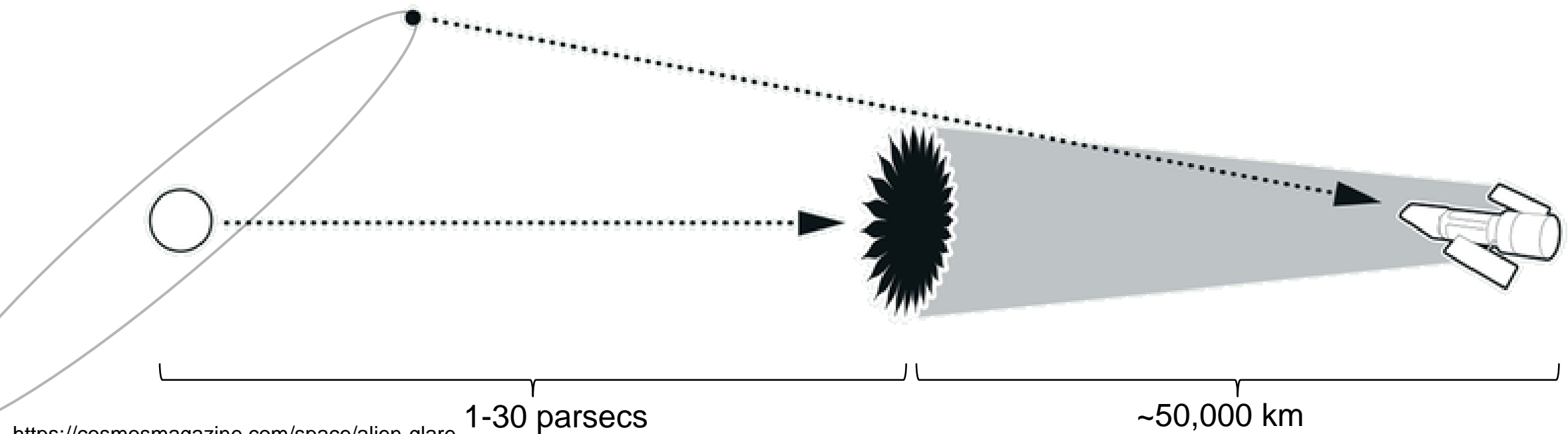
Stuart Shaklan, Carl Seubert,
Stefan Martin, Shannon Zareh,
Milan Mandic
*Jet Propulsion Lab,
California Institute of Technology*



Starshade concept



Exoplanet Exploration Program



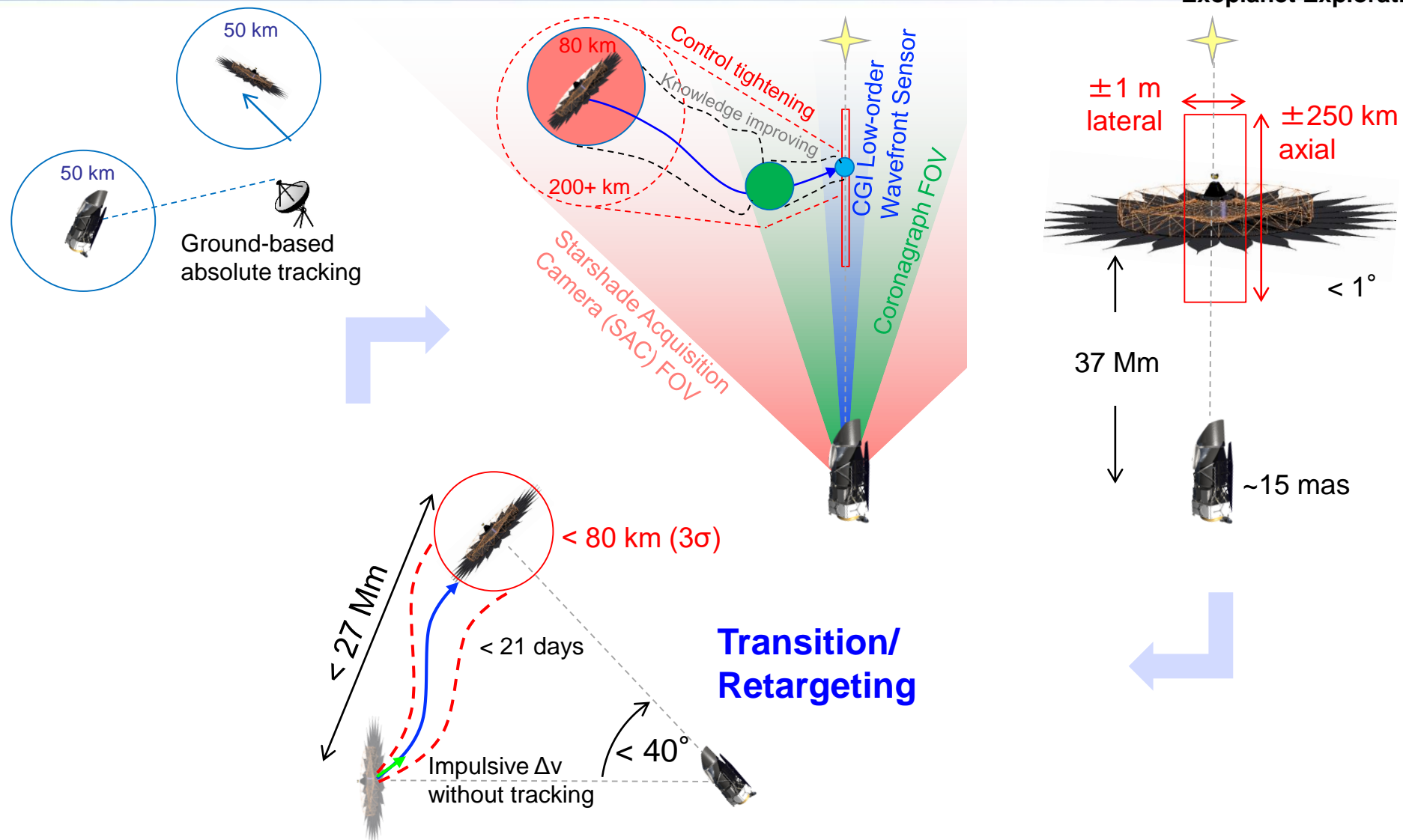


Initialization

Acquisition

Science

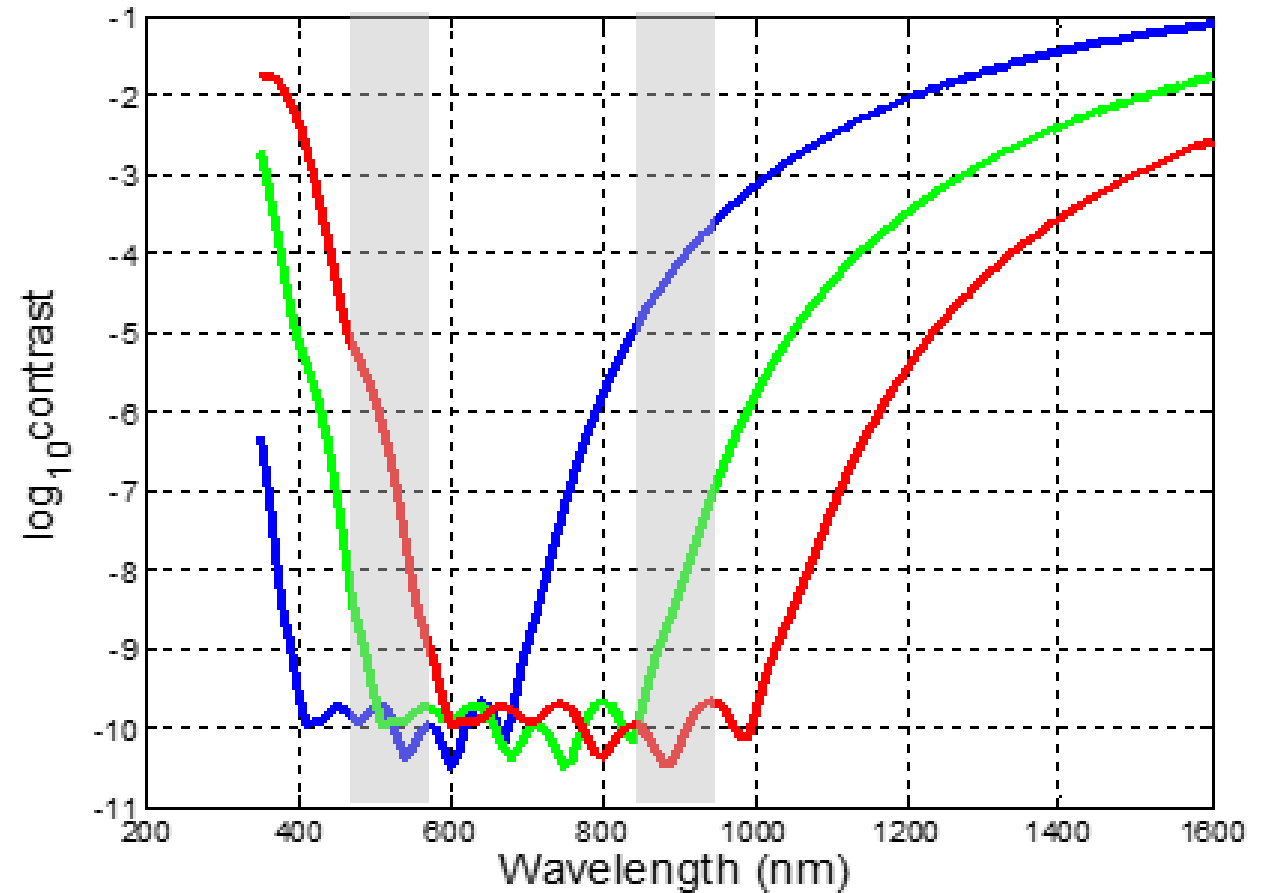
Exoplanet Exploration Program



- Starshades leak light out of their design band
- Diffracted out-of-band light has a characteristic “Poisson spot” in the pupil
- A pupil sensor (like the LOWFS) can use this spot to figure out the starshade position
- A laser can be used to figure out tip/tilt as well

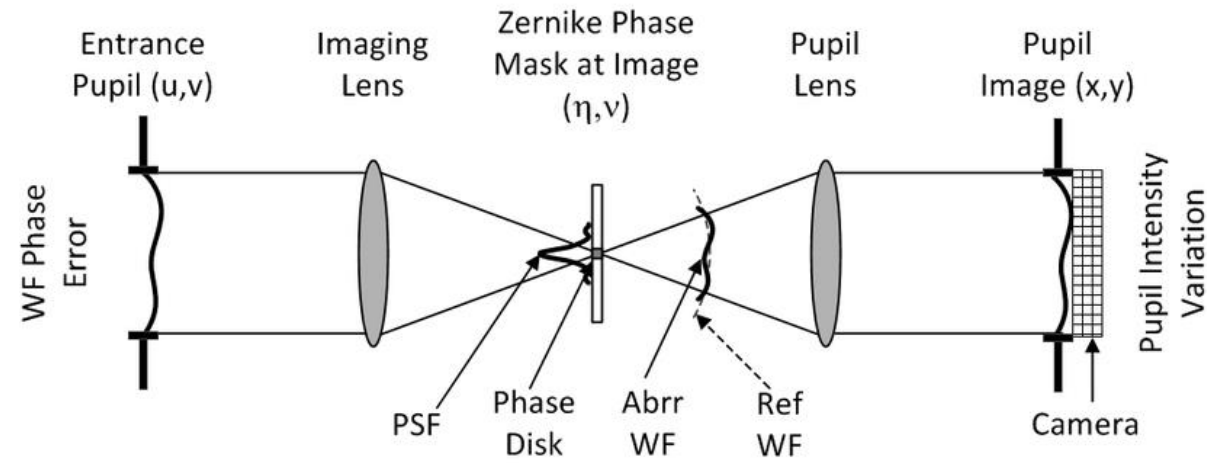
Good suppression at 500, bad at 950

Good suppression at 950, bad at 500

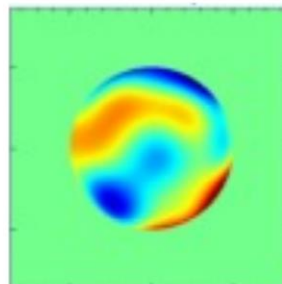


Zernike sensor

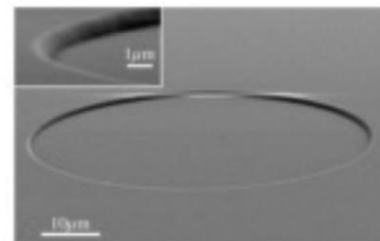
Exoplanet Exploration Program



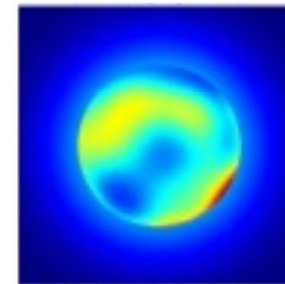
Wavefront error map



Phase mask



ZELDA meas.



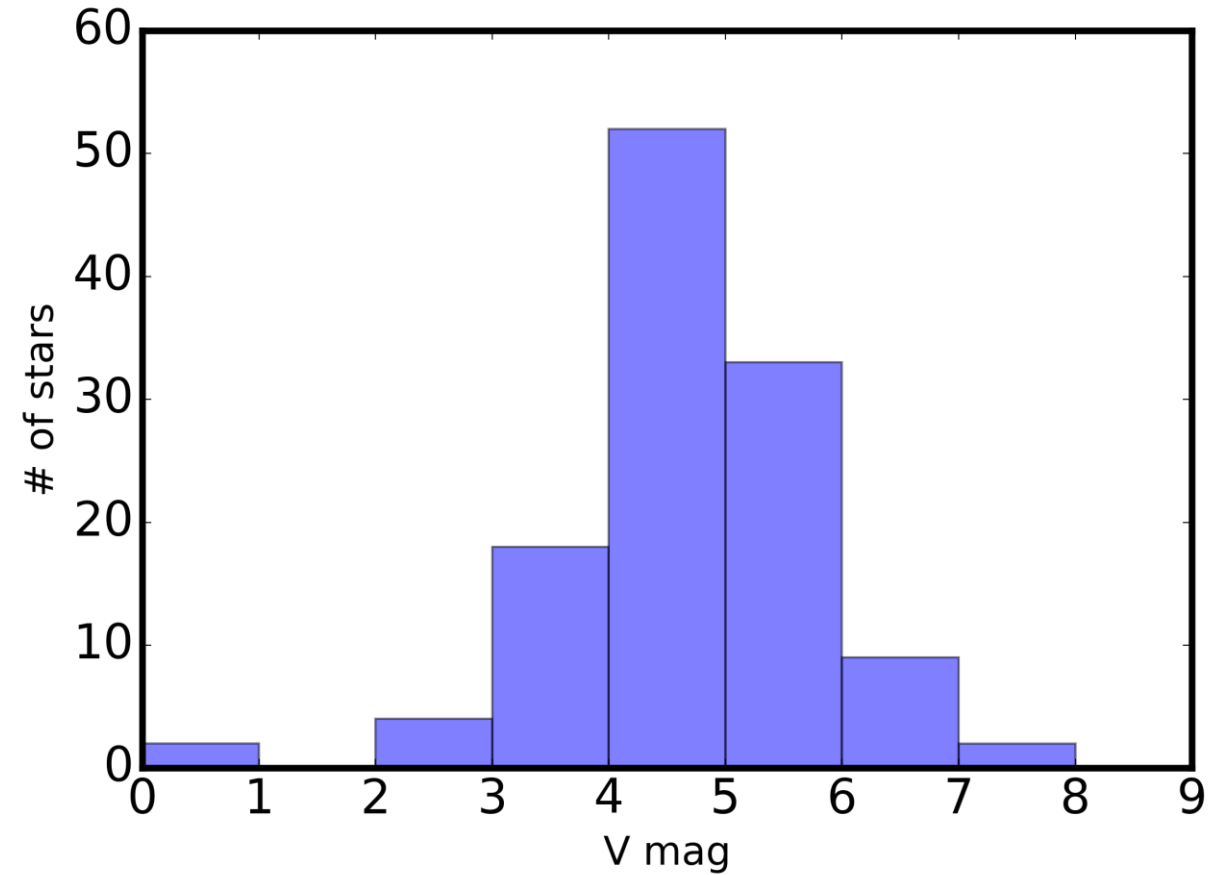


Do we have enough light to sense position/tilt?

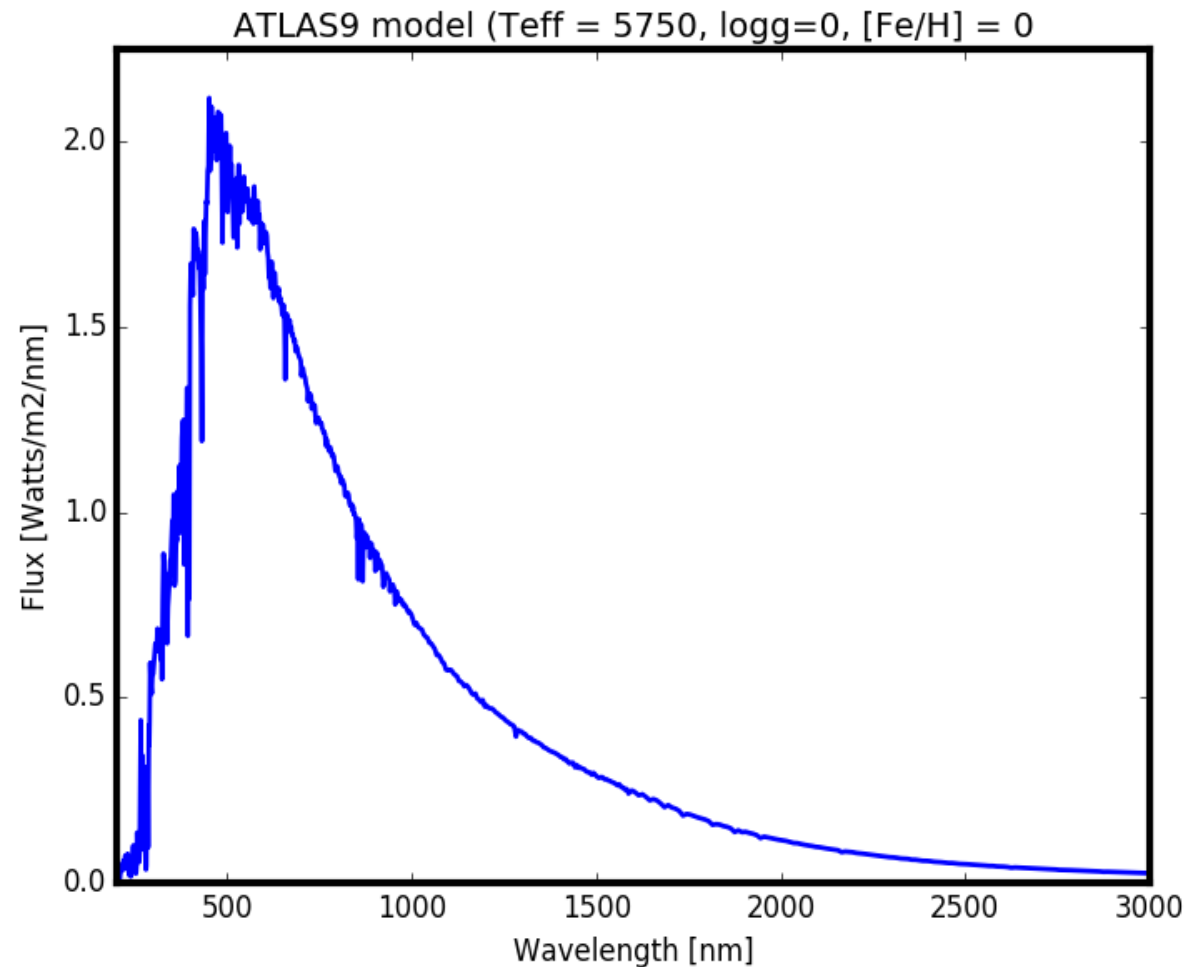


Exoplanet Exploration Program

- Need the starlight to sense the shear position
- At some star brightness, you run out of photons
- Post-starshade photons are what is important
- Starshade stars are very bright (mostly naked-eye visible)
- But there are losses through system (starshade, optics, camera, etc)



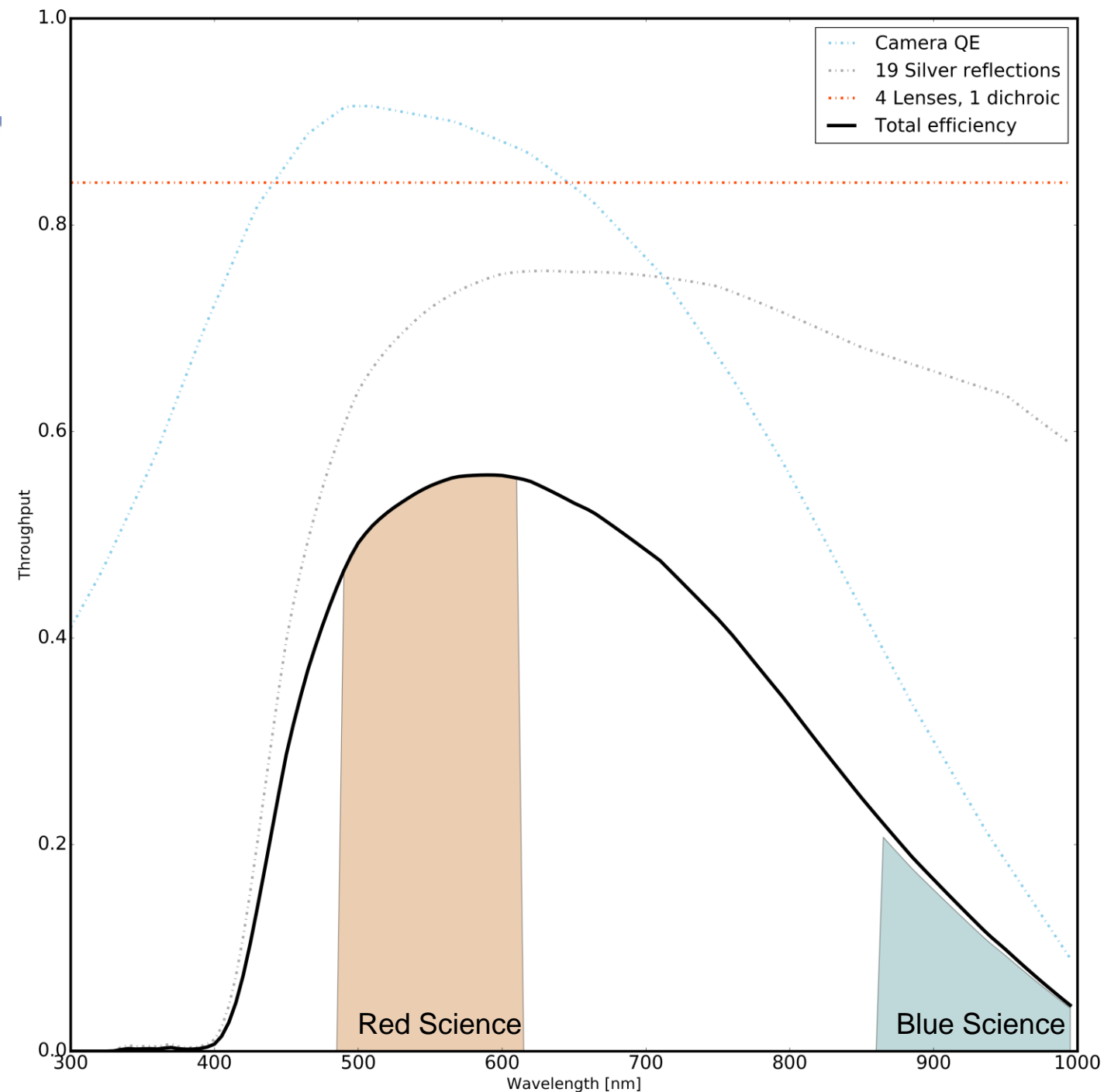
- ATLAS9 synthetic spectral atlas
- Sun-like star
 - $T_{\text{eff}} = 5750$
 - $\log g = 0.0$
 - $[\text{Fe}/\text{H}]$ (metal content) = 0
- Also:
 - Solar radius + distance
 - Magnitude (conversion)
- Checked power and photons/s using photometric zeropoints of stars, solar spectrum @ Earth, excellent agreement



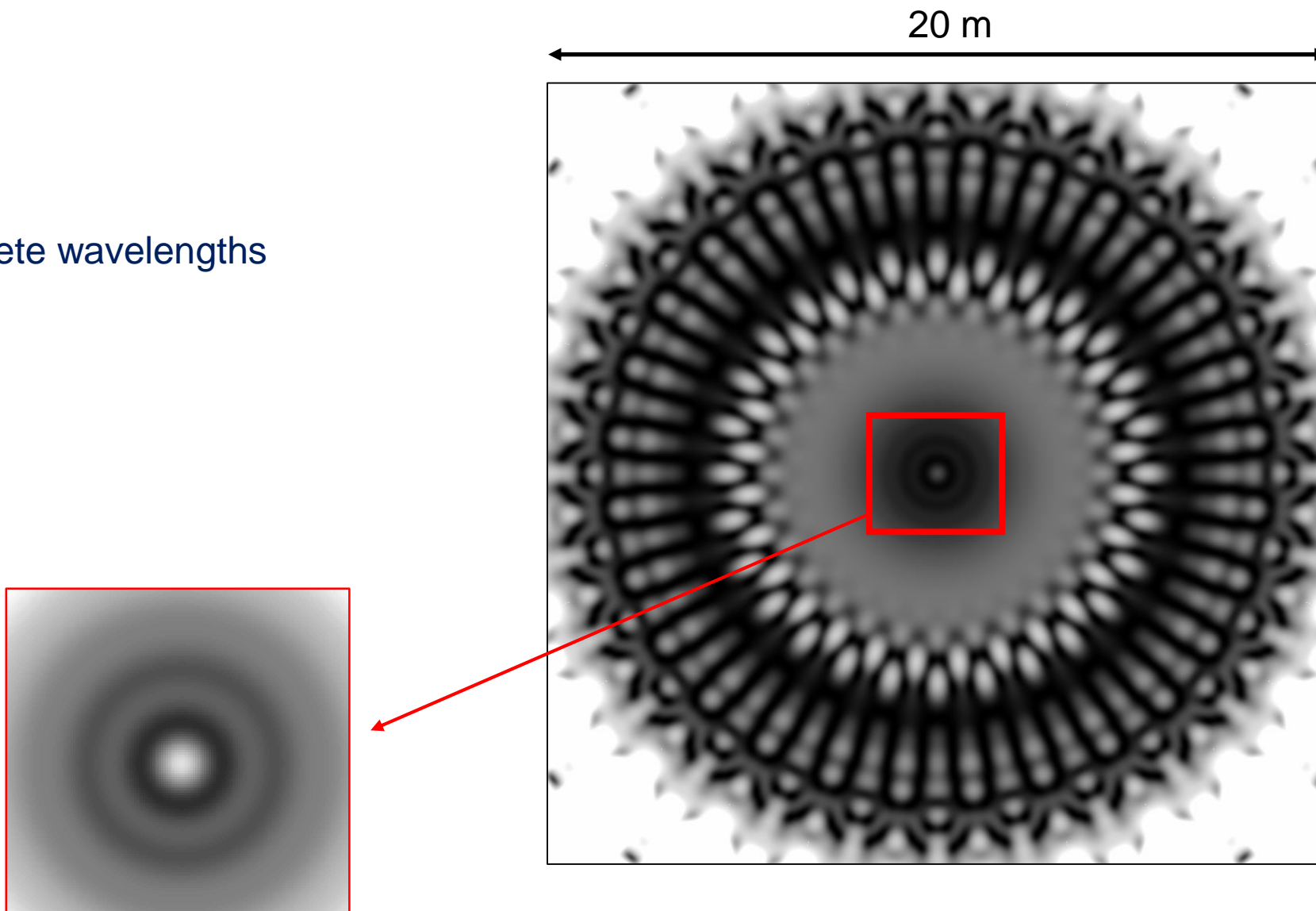


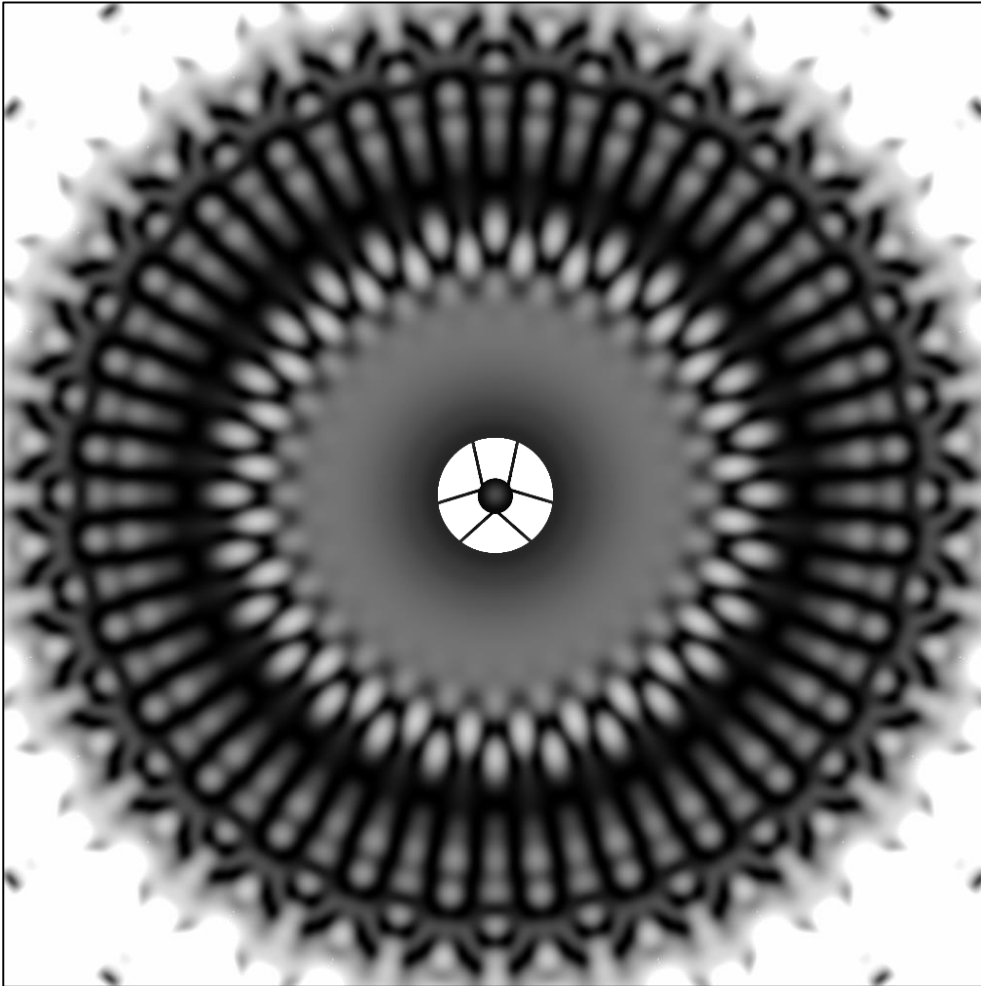
Cam/Throughput

- QE: CCD39-spectral response curve
- 16x16 format
- Read noise: 3e-/pix/frame (5e-/pix/frame at fast readout)
- Filter
 - 486-614 nm
 - Sloan z'
 - Rectangular shape
- 50% “other optics” throughput
 - 19 mirrors @ 97%
 - Dichroic @ 95%
 - 4 lenses @ 99%
 - =50%



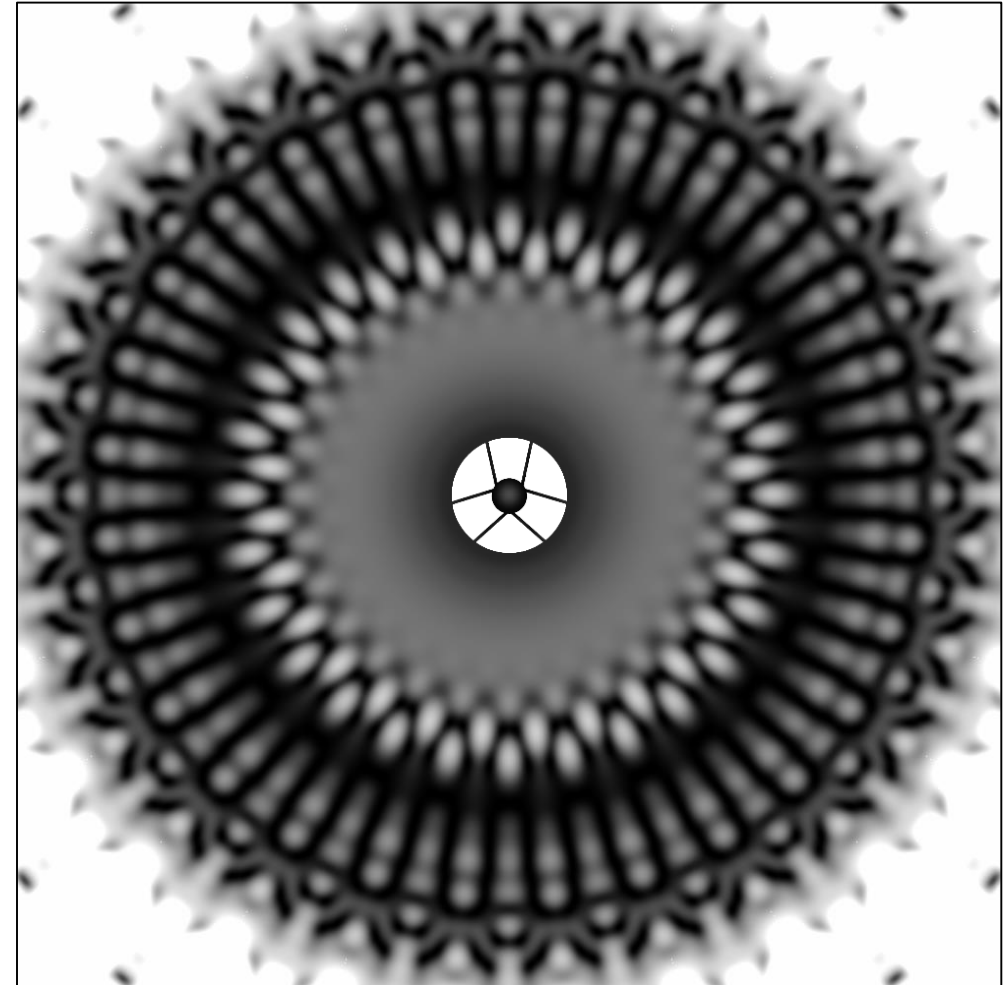
- JY21 model
- 20m x 20m
- 2cm/pix resolution
- Calculated at discrete wavelengths



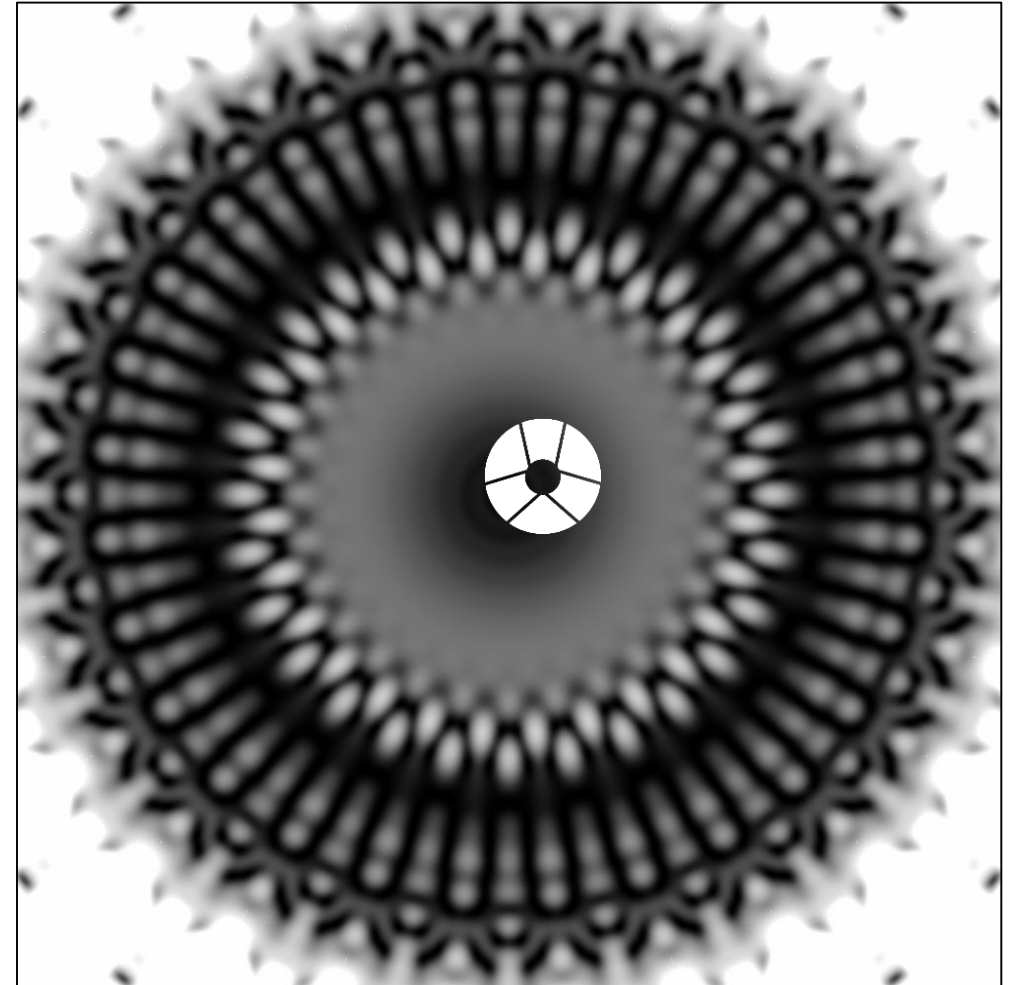


- How well can we sense the position of the starshade around a star of magnitude <6 , 8, 10 in science mode (in the shadow)?
- How much time do we need to get a measurement of the starshade position with 5 cm accuracy? 10cm?
- How does tip/tilt jitter affect this?

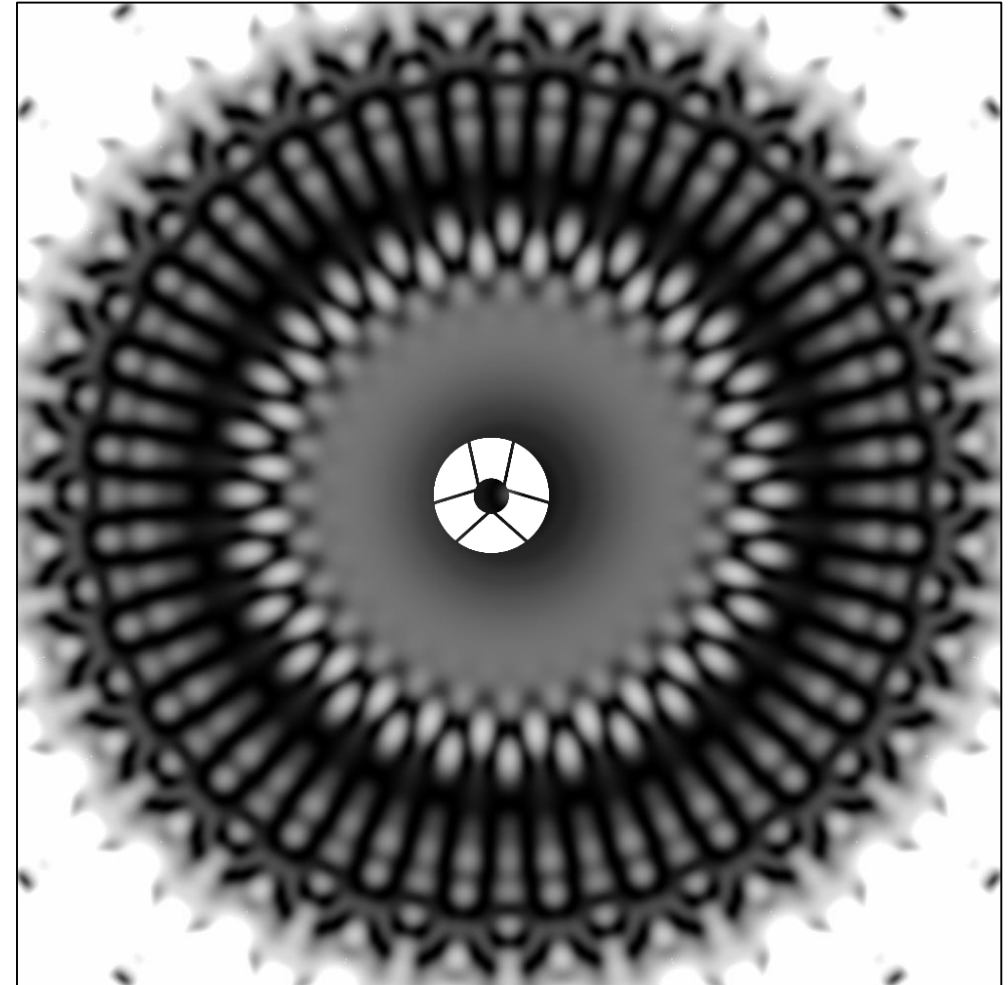
- Motion parameters
 - Starshade misalignment
 - Shear x (variable)
 - Shear y (variable)
 - Telescope tilt
 - Tilt x (0 mas)
 - Tilt y (0 mas)
 - Tilt jitter (**not relevant**)
- Camera
 - 3 electron readout noise
 - 1 second exposure time



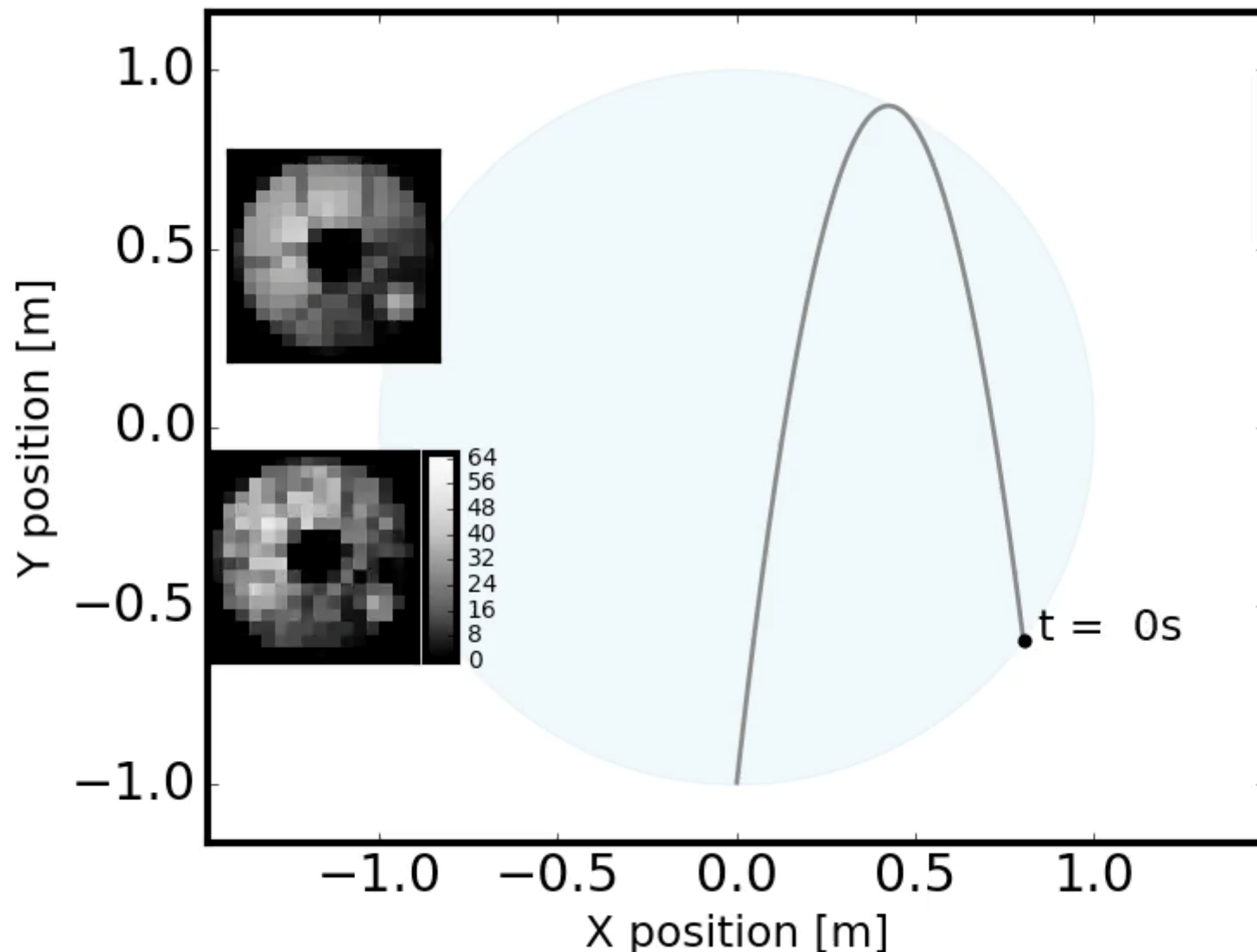
- Motion parameters
 - Starshade misalignment
 - Shear x (variable)
 - Shear y (variable)
 - Telescope tilt
 - Tilt x (0 mas)
 - Tilt y (0 mas)
 - Tilt jitter (**not relevant**)
- Camera
 - 3 electron readout noise
 - 1 second exposure time



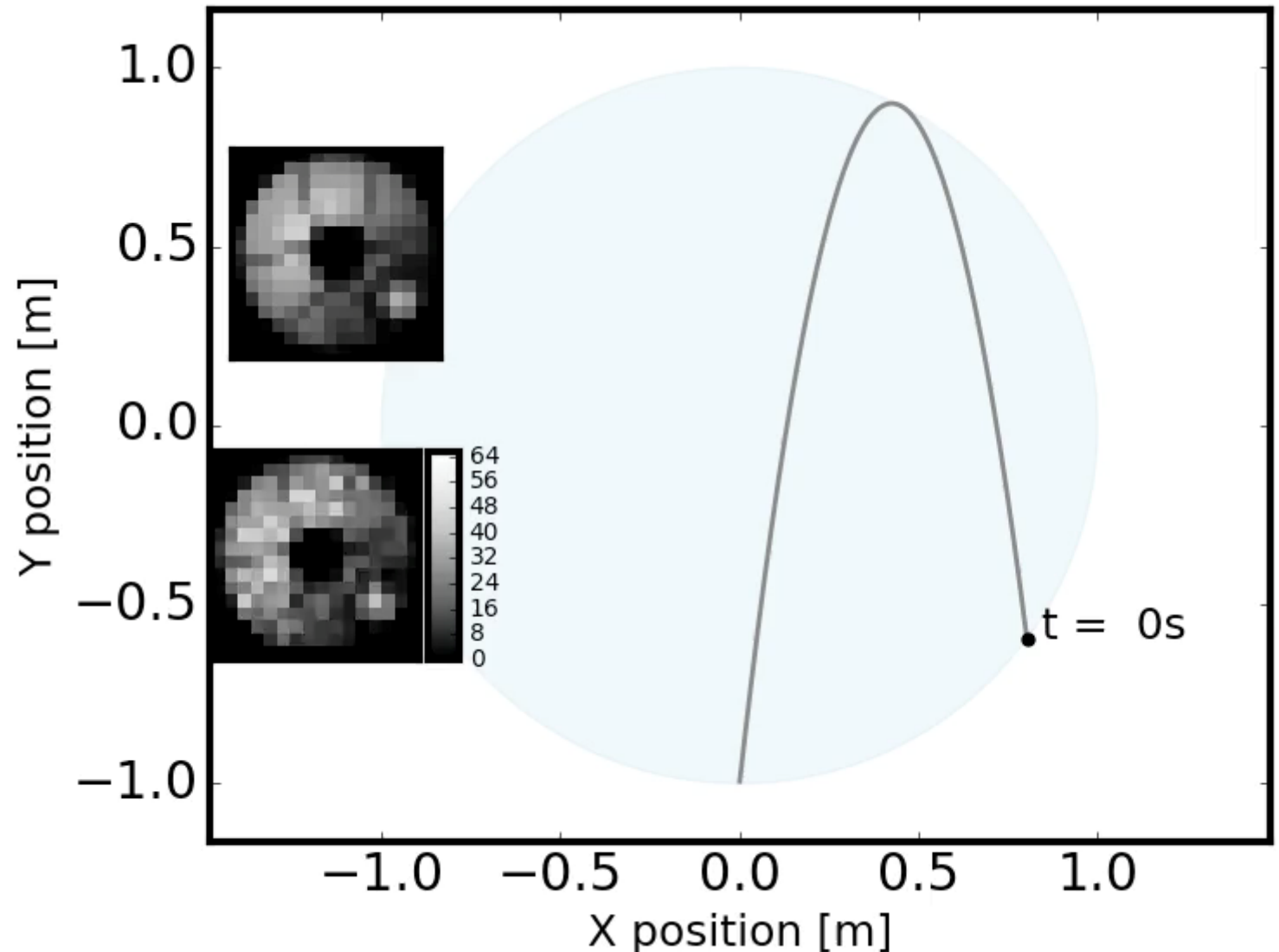
- Motion parameters
 - Starshade misalignment
 - Shear x (variable)
 - Shear y (variable)
 - Telescope tilt
 - Tilt x (0 mas)
 - Tilt y (0 mas)
 - Tilt jitter (**not relevant**)
- Camera
 - 3 electron readout noise
 - 1 second exposure time



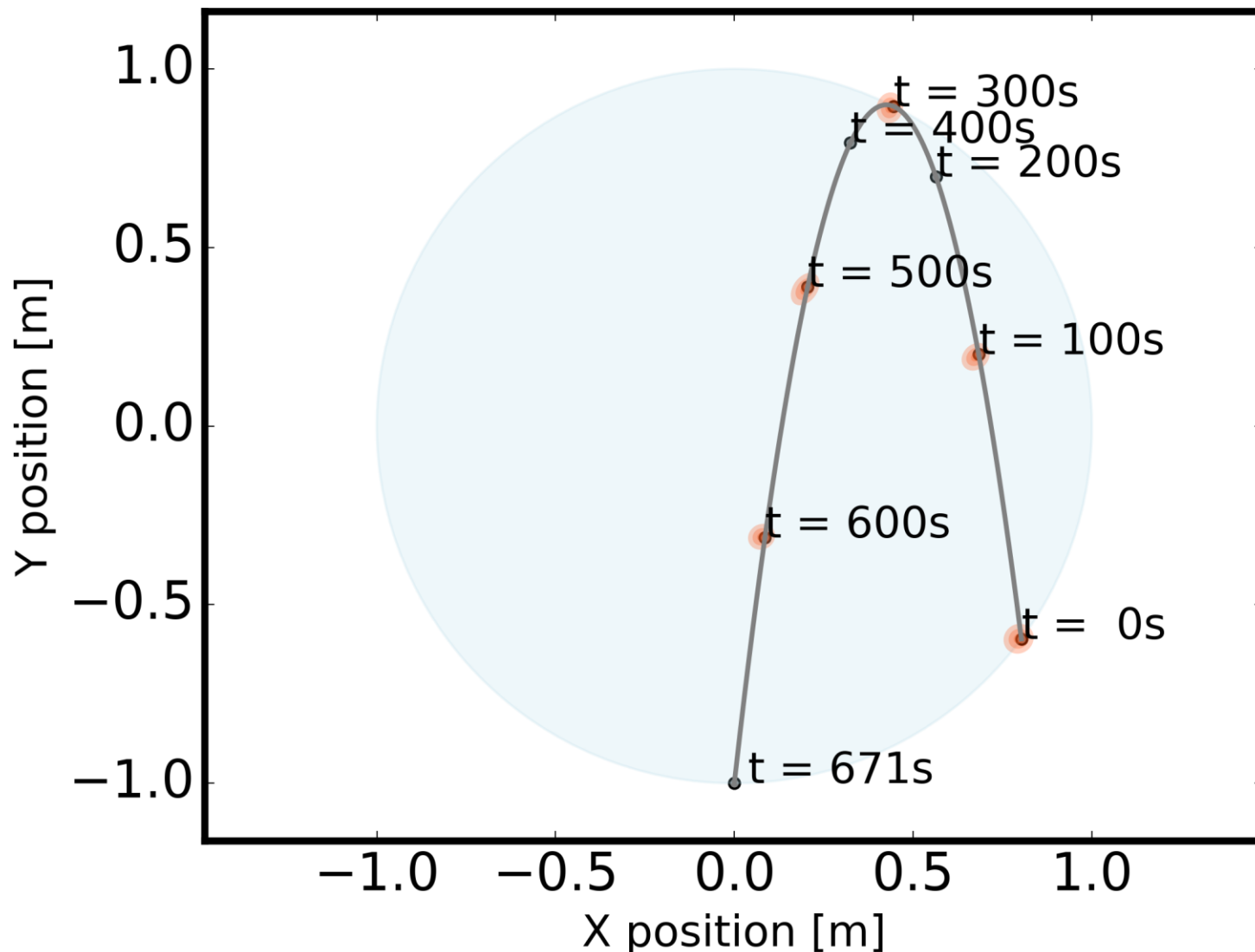
- Trajectory maneuver data from C. Seubert
- Within 1 m science “deadband”
- Top is perfect image
- Bottom is with noise (Poisson and read), basically **what LOWFS would see in 1 s of read time**



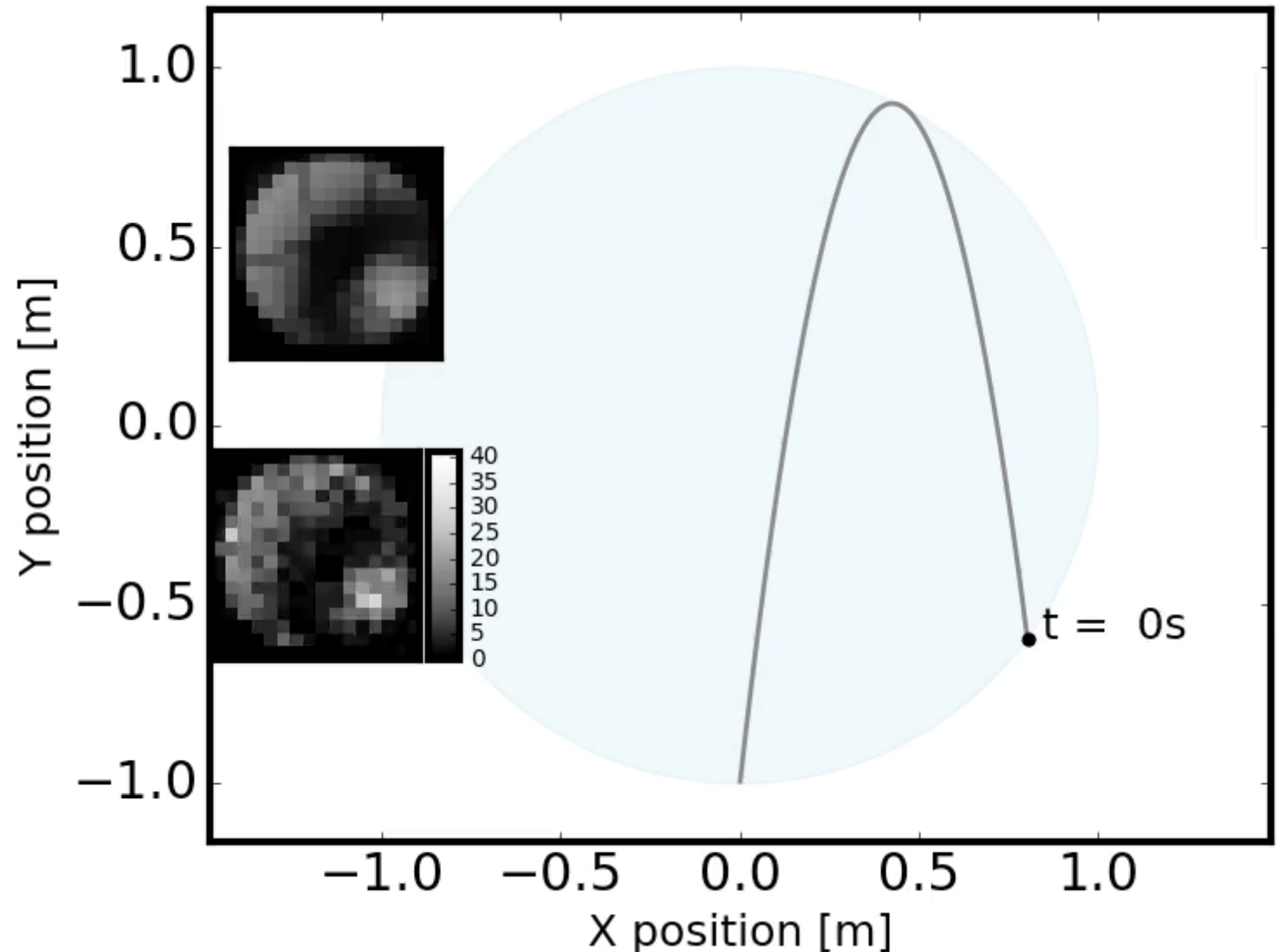
- Generate 1000 1s noisy images at a trajectory point
- Match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → save shear positions
- Get mean and std.dev of different shear positions



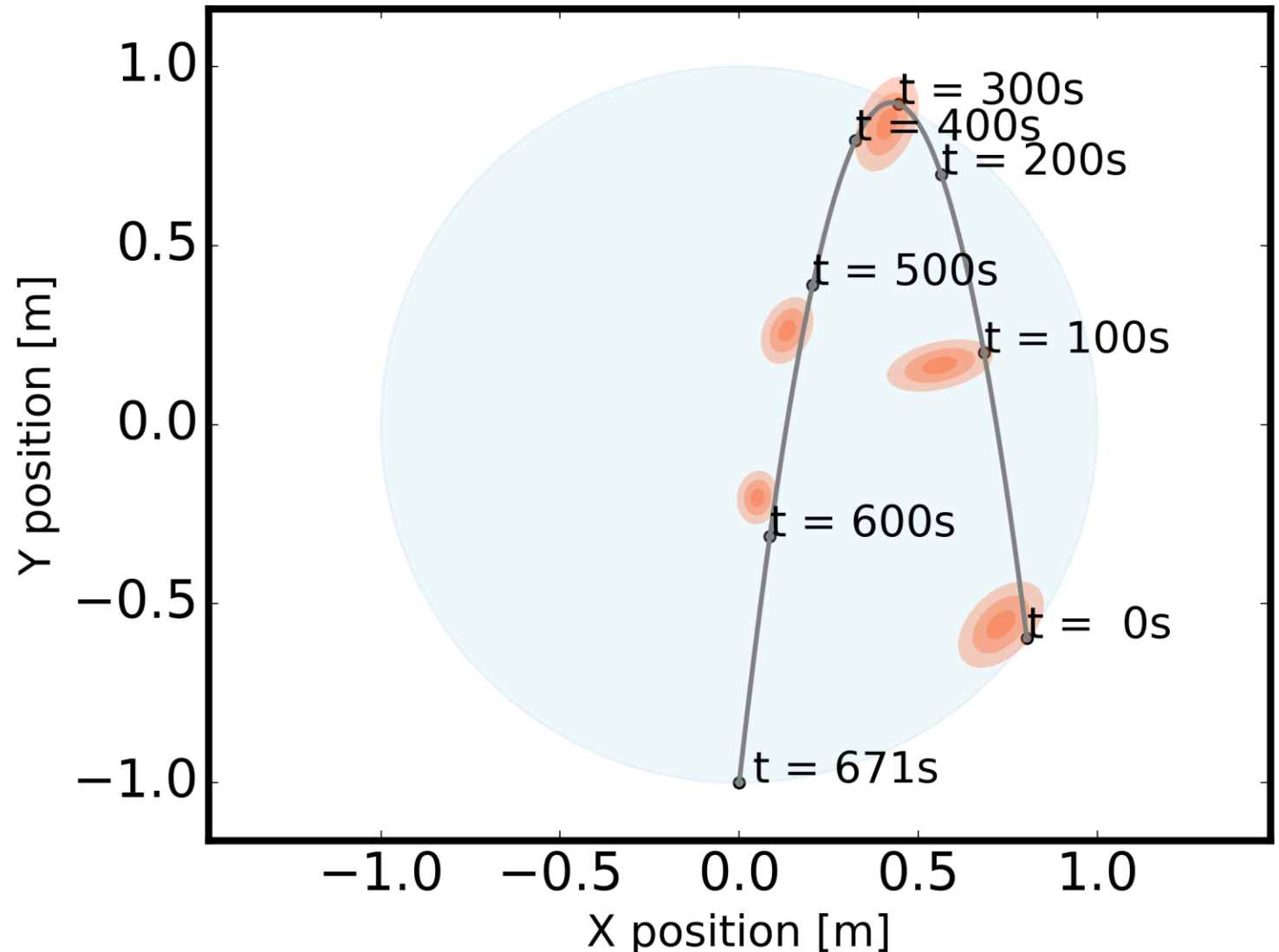
- Generate 1000 1s noisy images at a trajectory point
- Match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → save shear positions
- Get mean and std.dev of different shear positions (in this case, 3 cm error)



- Trajectory maneuver data from C. Seubert
- Within 1 m science “deadband”
- Top is perfect image
- Bottom is with noise (Poisson and read), basically what LOWFS would see



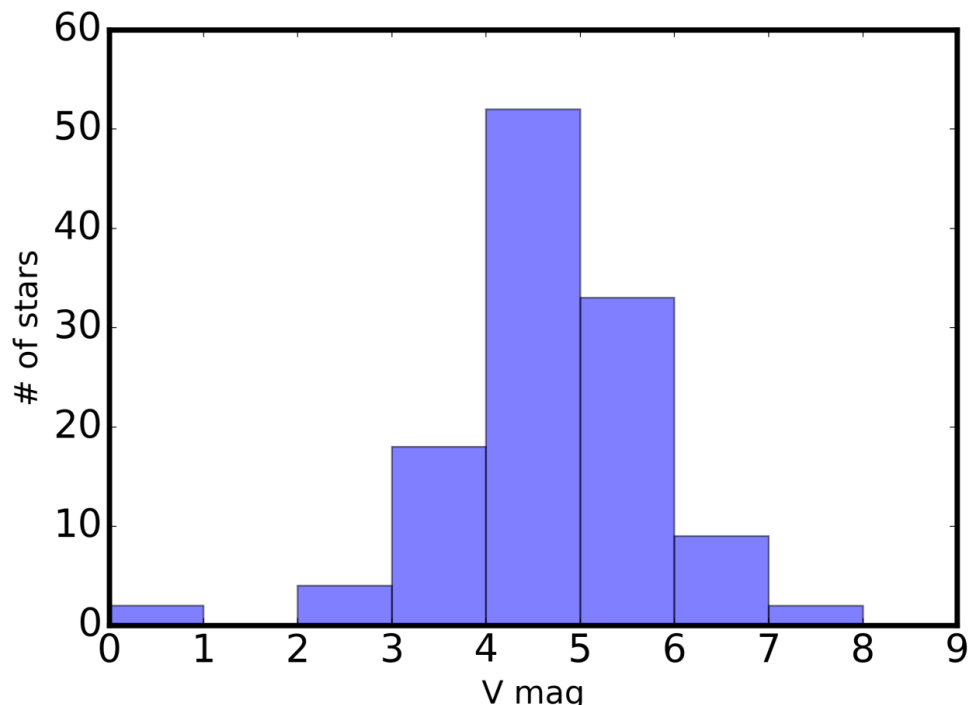
- Generate 1000 1s noisy images at a trajectory point
- Match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → save shear positions
- Get mean and std.dev of different shear positions (in this case, 7 cm error)



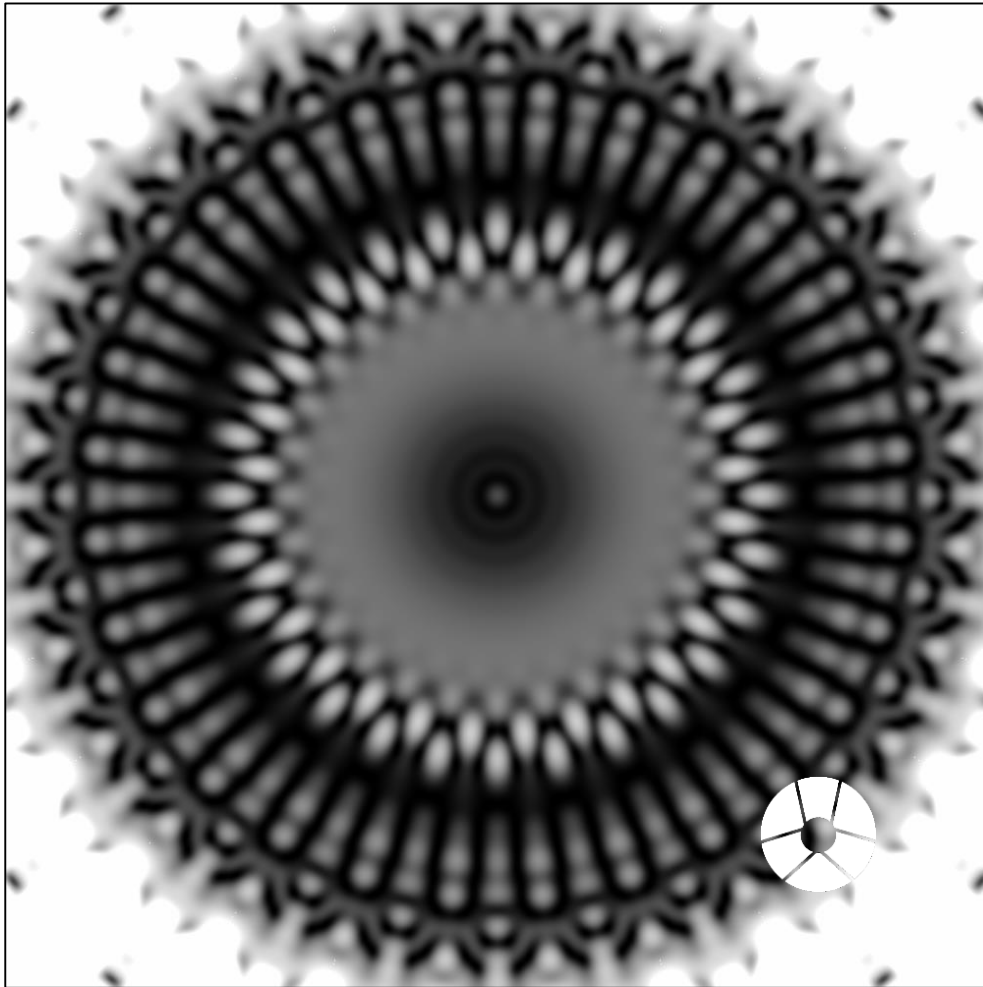
Conclusions

Exoplanet Exploration Program

- For all red science, can sense position to <5cm in <1s
- For blue science, can do so for stars <6 mag
- Tip tilt corruption of shear signal is not an issue for 15 mas jitter

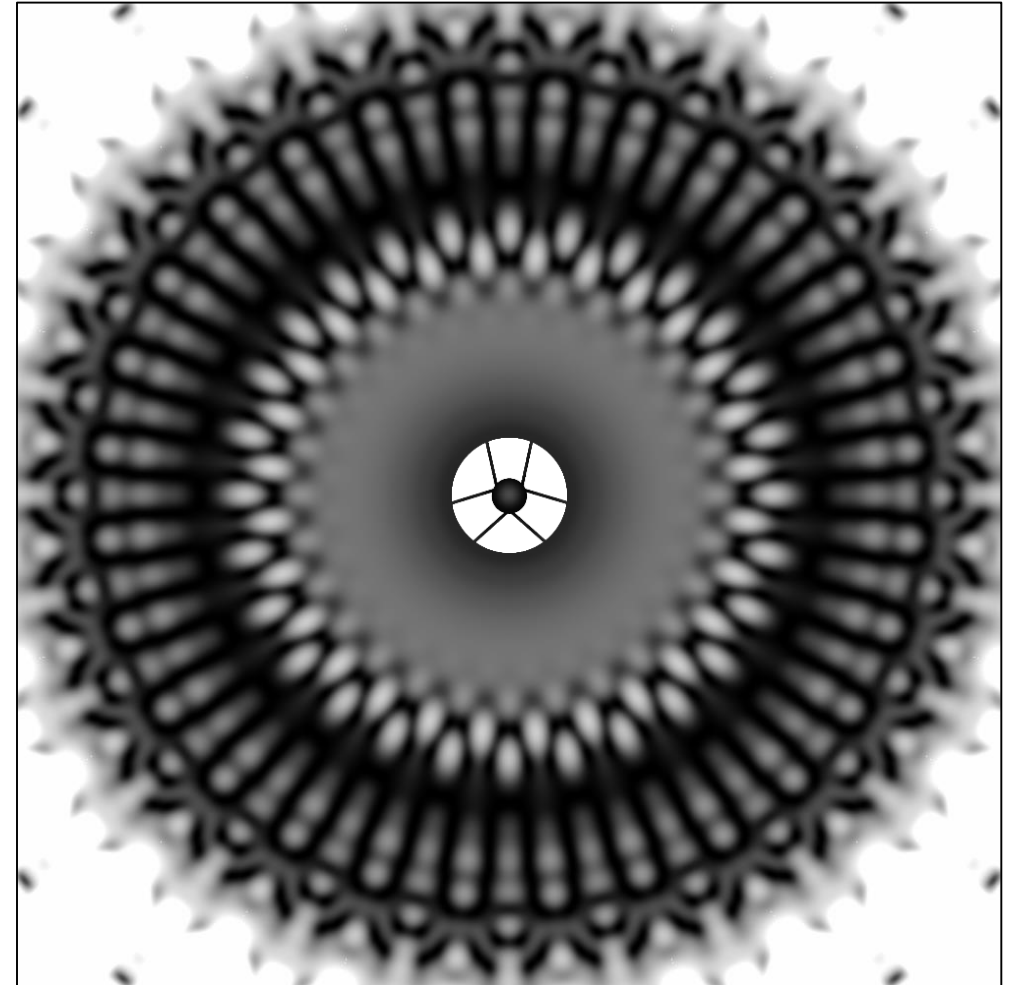


| Star magnitude (Solar SED) | Open shutter time (s) needed for red science 1 sigma uncertainty of <5 cm | Open shutter time (s) needed for blue science 1 sigma uncertainty of <5 cm |
|----------------------------|--|---|
| 8 | 1 (2cm) | 6.25 |
| 7 | 0.4 | 2.5 |
| 6 | 0.16 | 1 (3 cm) |
| 5 | 0.064 | 0.4 |
| 4 | 0.0256 | 0.16 |
| 3 | 0.01 | 0.064 |

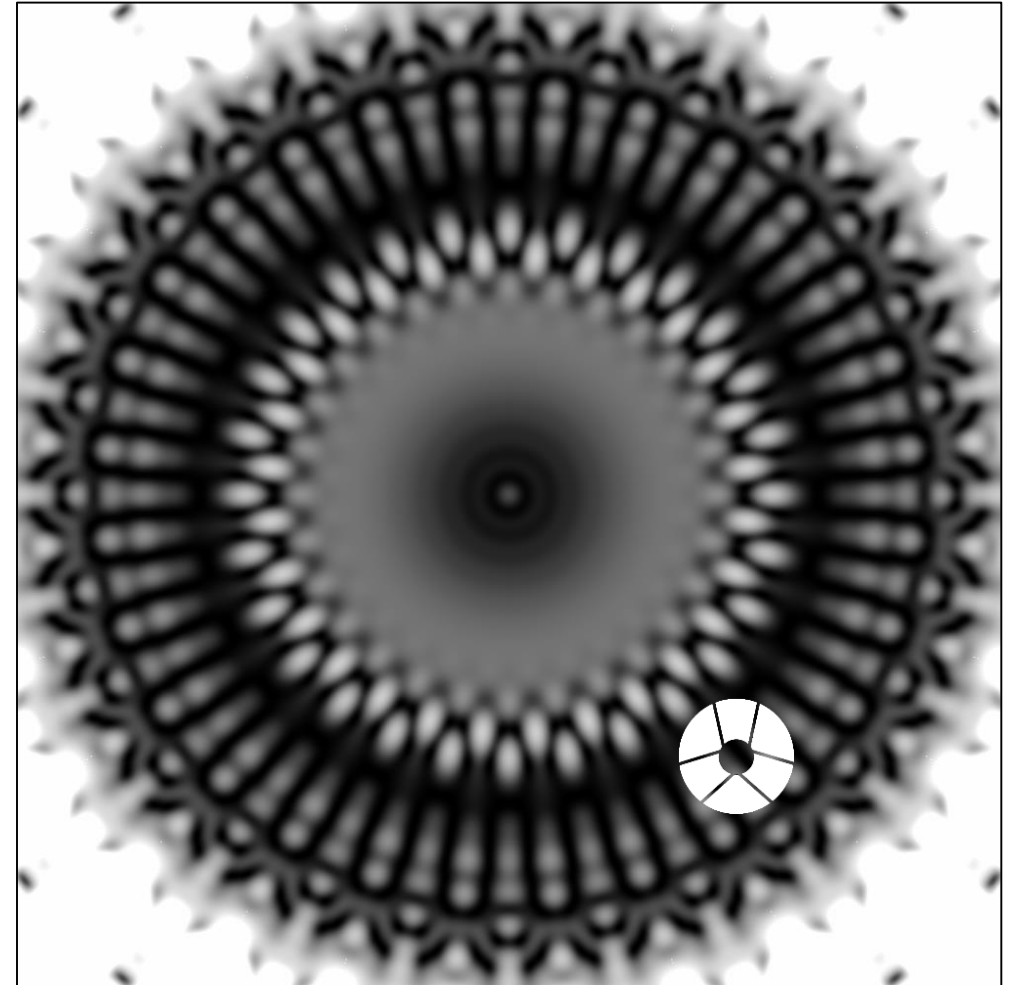


- Can we acquire the dark hole without “putting”?
- How well can we sense the position of the starshade around a star of magnitude 6, 8, 10 when we are **close (<10 m) , but not on**, the center spot?
- How much time do we need to get a measurement of the starshade position with 5 cm accuracy? 10cm?

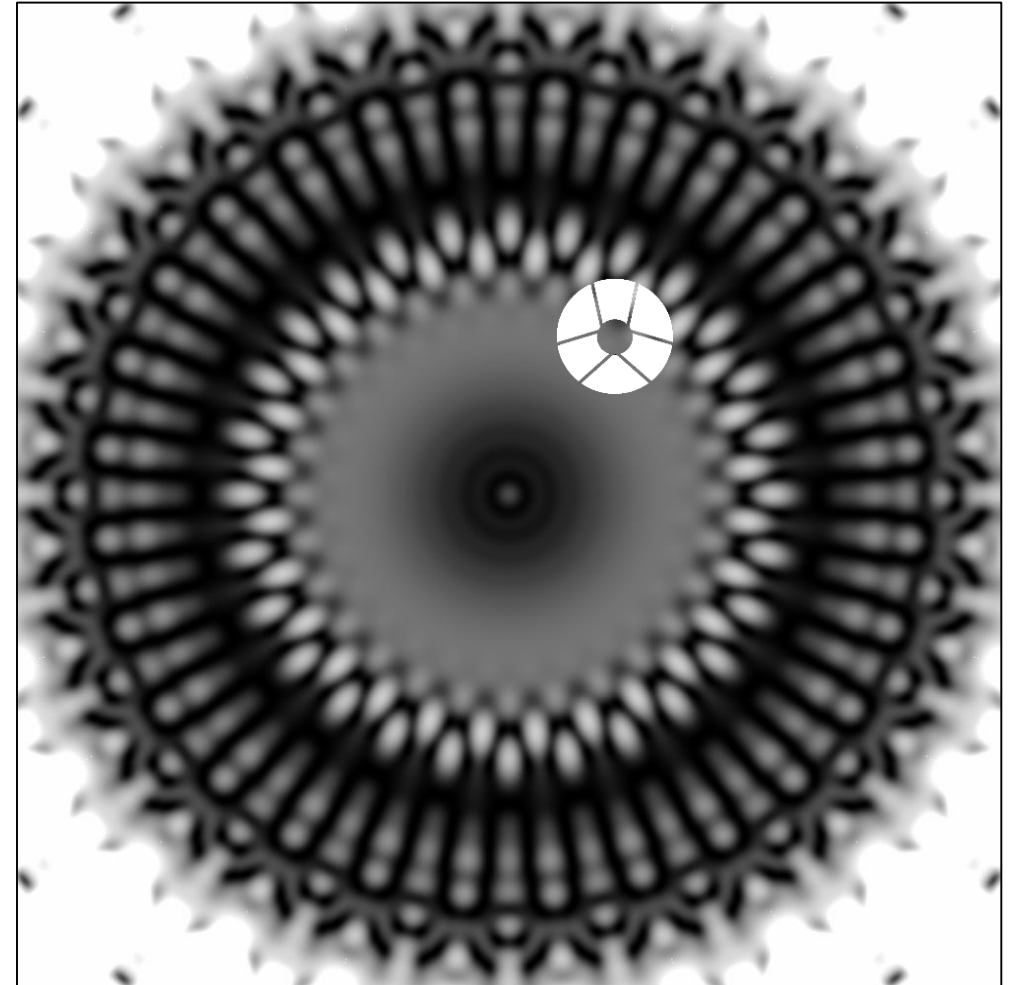
- Motion parameters
 - Starshade misalignment
 - Shear x (variable)
 - Shear y (variable)
 - Telescope tilt
 - Tilt x (0 mas)
 - Tilt y (0 mas)
 - Tilt jitter (**15 mas 1 σ**)
- Camera
 - 3 electron readout noise
 - 1 second exposure time
- Filter
 - Stick to red science band



- Motion parameters
 - Starshade misalignment
 - Shear x (variable)
 - Shear y (variable)
 - Telescope tilt
 - Tilt x (0 mas)
 - Tilt y (0 mas)
 - Tilt jitter (**15 mas 1 σ**)
- Camera
 - 3 electron readout noise
 - 1 second exposure time
- Filter
 - Stick to red science band



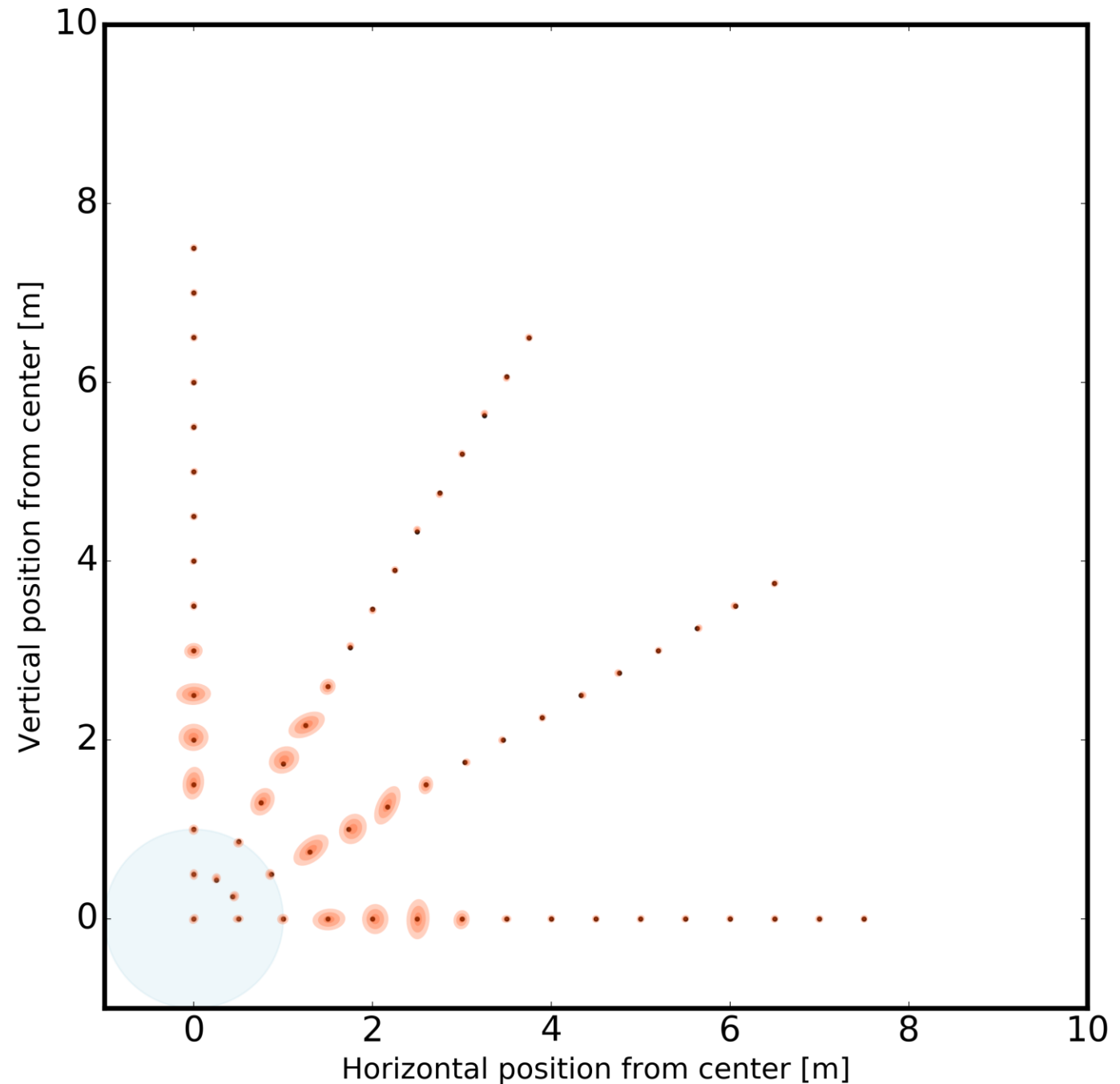
- Motion parameters
 - Starshade misalignment
 - Shear x (variable)
 - Shear y (variable)
 - Telescope tilt
 - Tilt x (0 mas)
 - Tilt y (0 mas)
 - Tilt jitter (**15 mas 1 σ**)
- Camera
 - 3 electron readout noise
 - 1 second exposure time
- Filter
 - Stick to red science band





LOWFS signal, 8th magnitude star

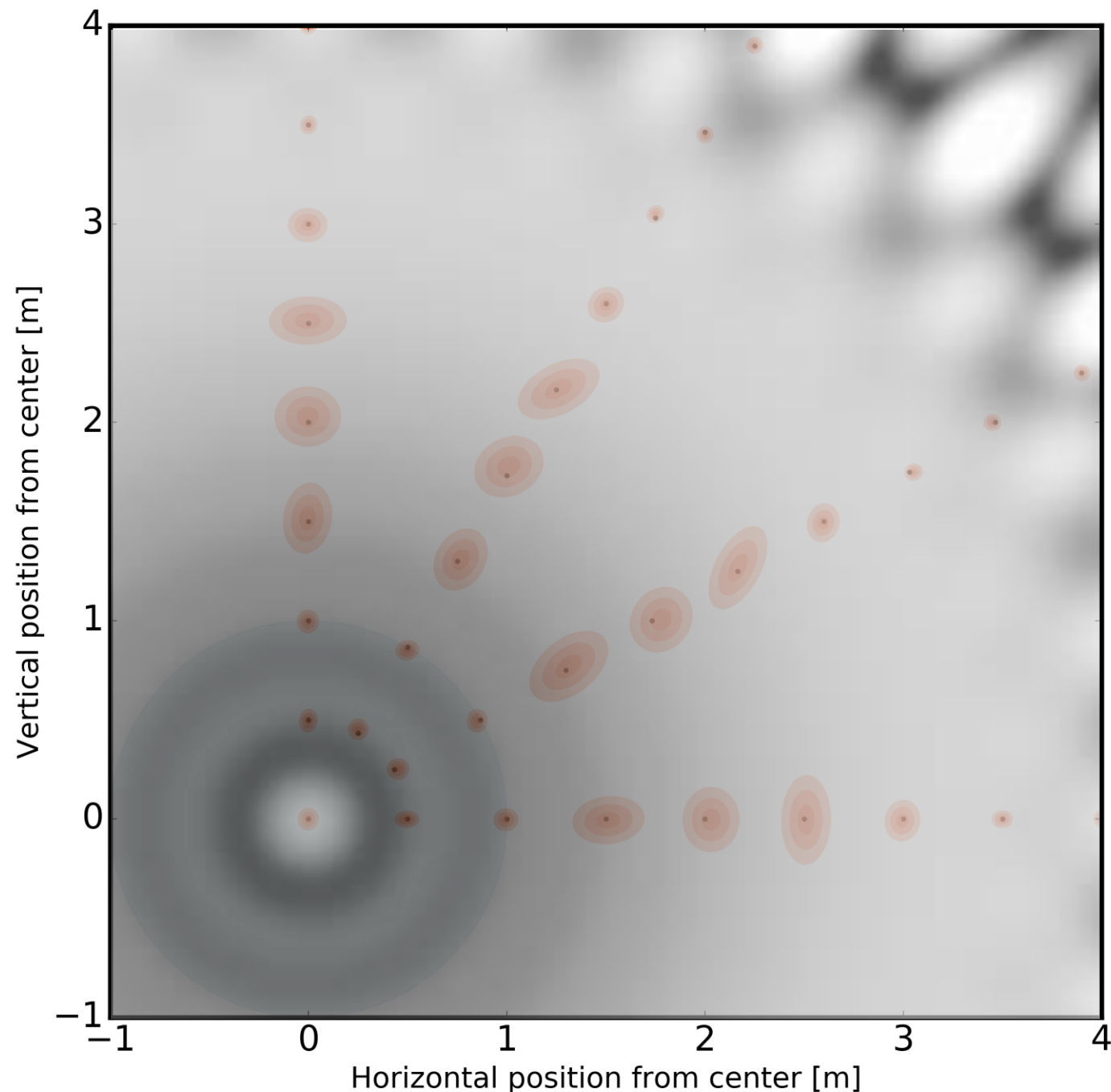
- Generate 400 1s noisy images at different radial positions
- match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → corresponding shear position
- Get mean and std.dev of different shear positions

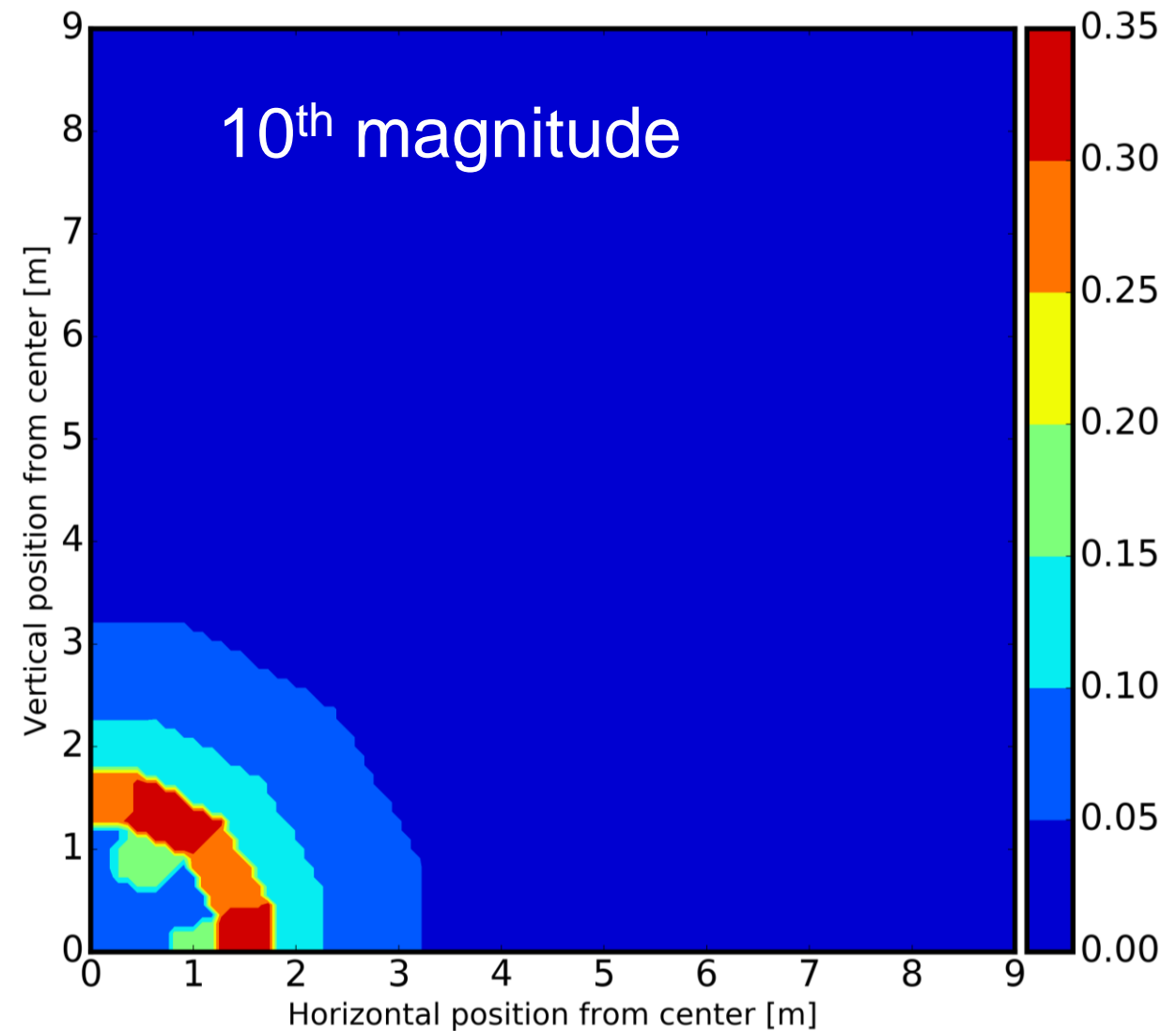
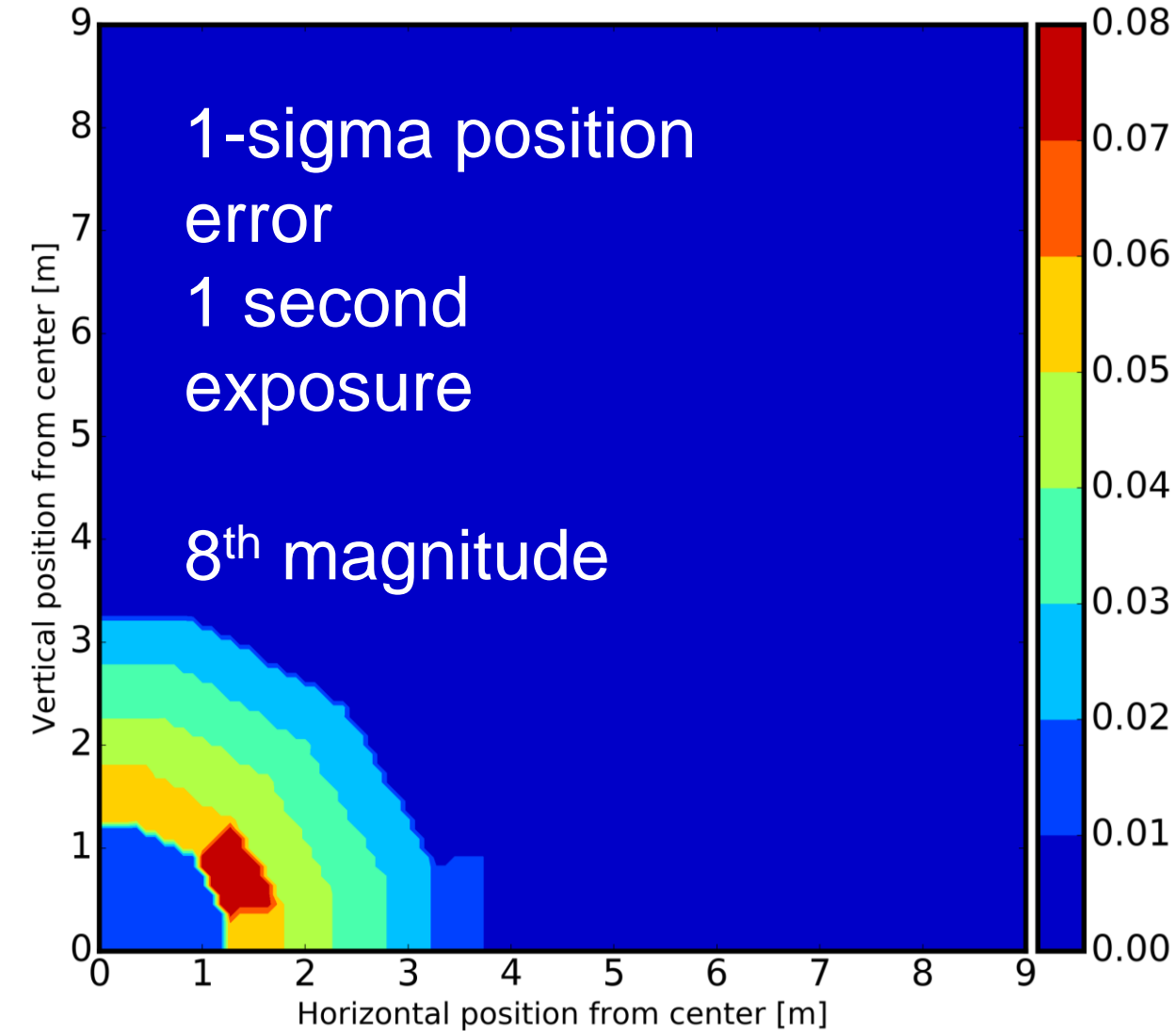




LOWFS signal, 8th magnitude star

- Generate 400 1s noisy images at different radial positions
- match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → corresponding shear position
- Get mean and std.dev of different shear positions







Conclusions



Exoplanet Exploration Program

- **Easy to sense shade position to $<5\text{cm}$ in 1 second with stars of 8th mag or brighter, out to 8.5 meters**
- 10th mag is (mostly) fine too
- There is one region between 1-3 meters away where the the gradient is very constant, and it's hard to get a good absolute position for faint stars—but at that point, just follow the gradient to the center



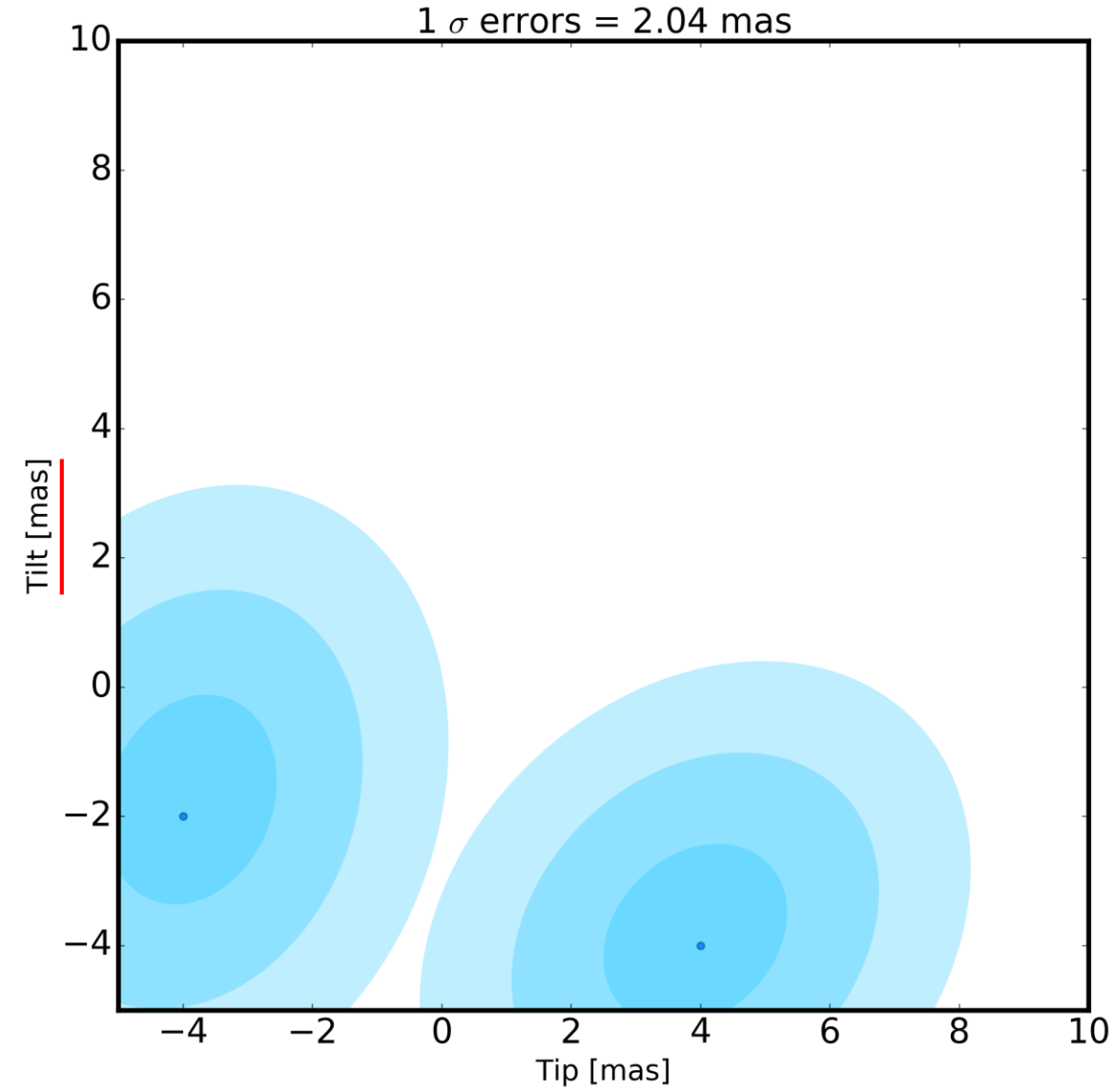
Sensing tip/tilt and shear measurements with the LOWFS and starlight



Exoplanet Exploration Program

- Is there enough starlight to sense slow tip/tilt aberrations with the LOWFS?
- Is there enough starlight to sense fast tip/tilt aberrations with the LOWFS?

- Solve for shear and tilt simultaneously using matched filter
- Red science band (best case)
- **6th mag star, 1 s integration time**
- **2.04 mas rms**



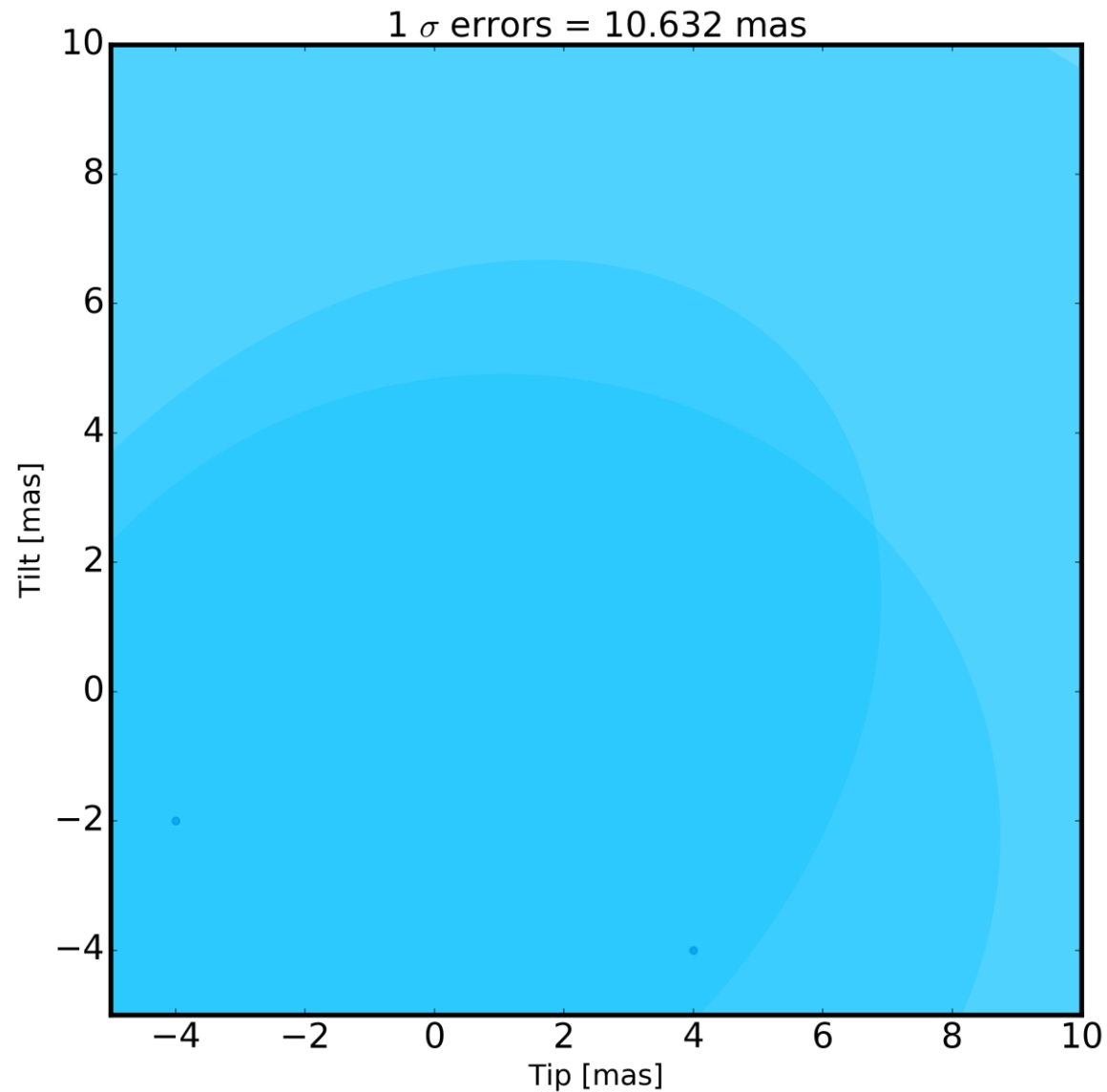


Fast tip/tilt aberrations



Exoplanet Exploration Program

- Solve for shear and tilt simultaneously using matched filter
- No jitter in this simulation
- **6th mag star, 0.01 s integration time**
- **Railed**
- **Not feasible/useless**



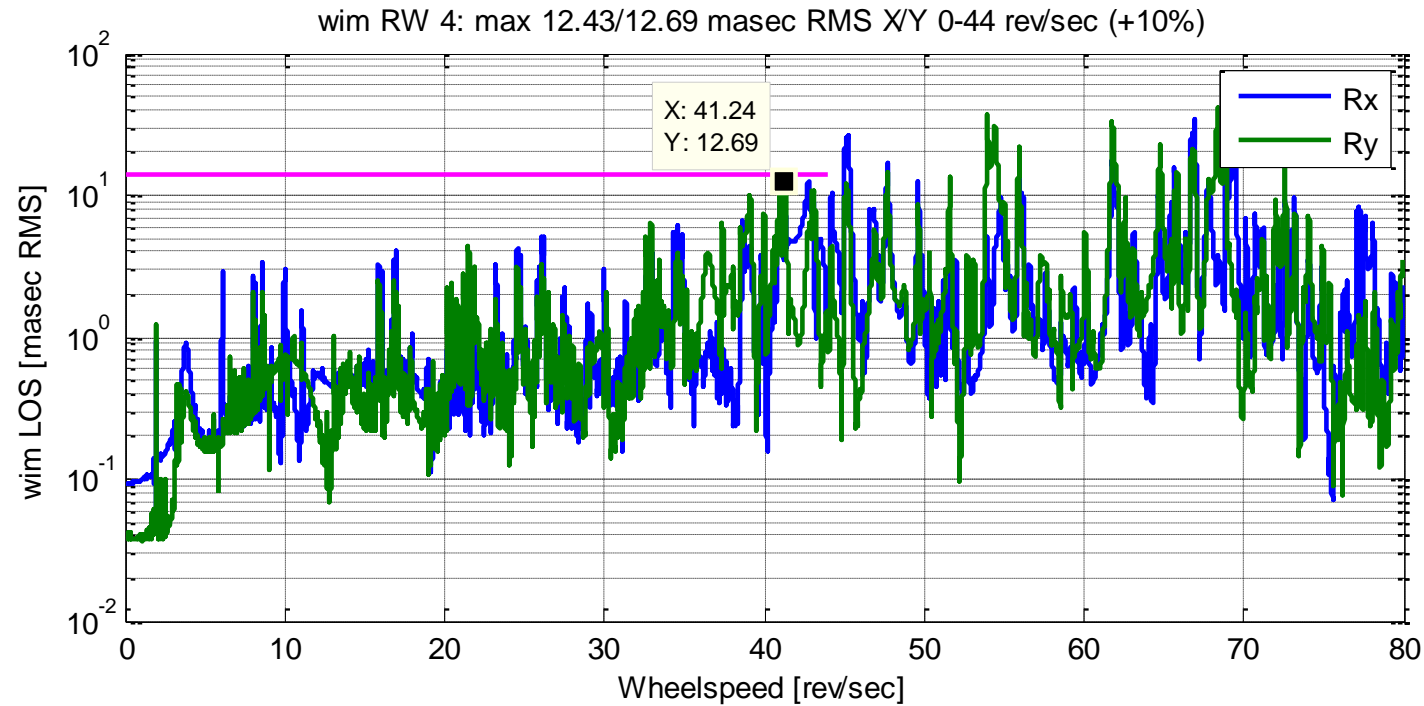


Sensing tip/tilt and shear measurements with the LOWFS and starlight

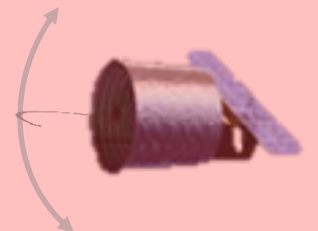
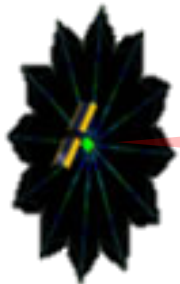


Exoplanet Exploration Program

- Is there enough starlight to sense slow tip/tilt drifts with the LOWFS? **Yes, barely**
- Is there enough starlight to sense fast tip/tilt jitter with the LOWFS? **No, not even close**



- How well can we sense tip/tilt error using the laser?
- How much open shutter time do we need to get a measurement of the tip/tilt position to a few mas?
- How does a shear signal in the beam affect this?



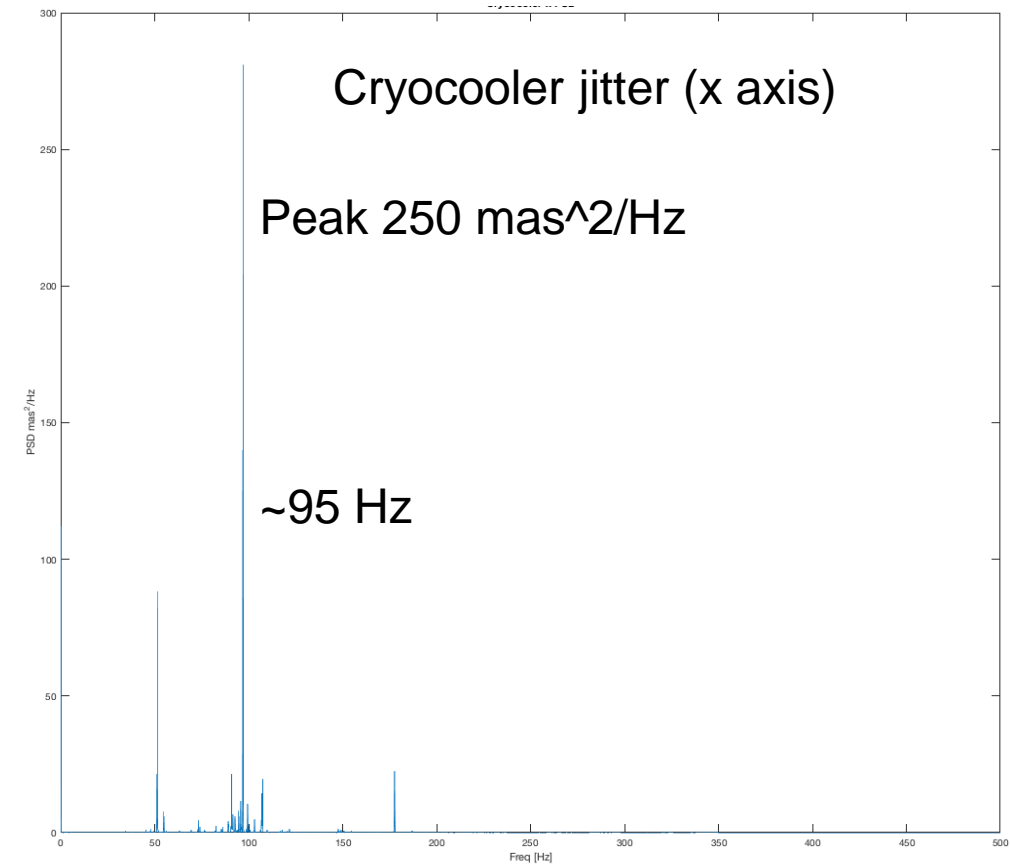
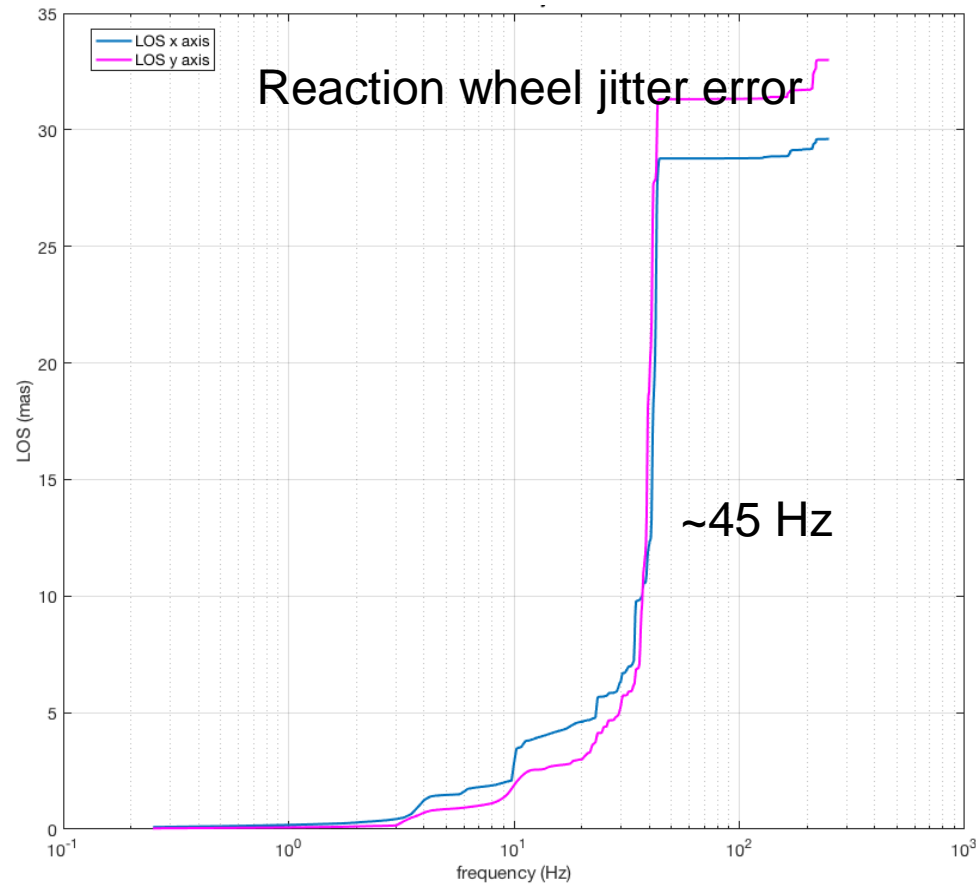


Main jitter terms in WFIRST



Exoplanet Exploration Program

From M. Mandic



Takeaway – to control the ~95 Hz jitter, need to sense at ~1kHz (maximum camera

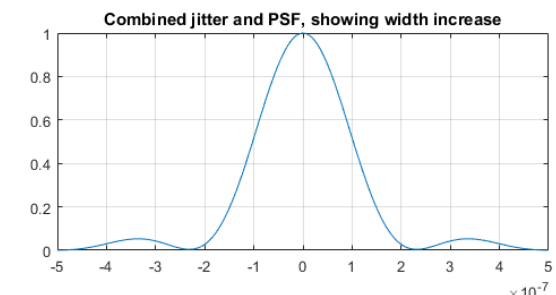
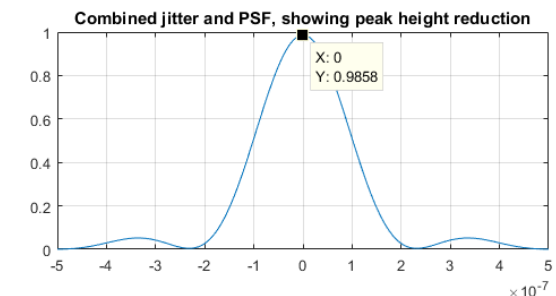
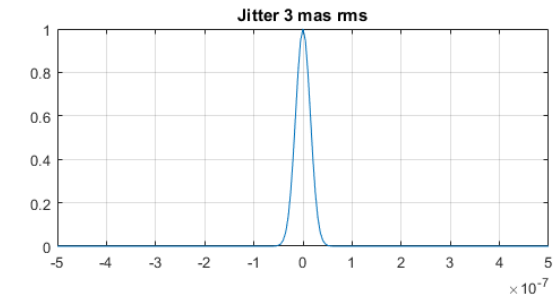
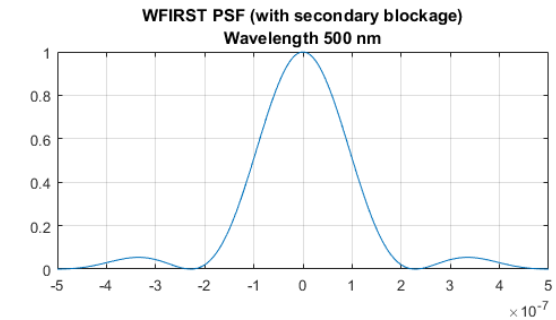


Effects of jitter



Exoplanet Exploration Program

| Science wavelength | Jitter (1 sigma) | Peak PSF amplitude (%) |
|--------------------|------------------|------------------------|
| 500 | 14 mas | 78 |
| 500 | 10 mas | 87 |
| 500 | 5 mas | 96 |
| 500 | 2.5 mas | 99 |
| 850 | 14 | 91 |
| 850 | 10 | 95 |
| 850 | 5 | 99 |



Conclusion: residual jitter of 5 mas: minimal effect on science

Corollary : even if we do nothing, it should be ok



Assumptions and sanity checks

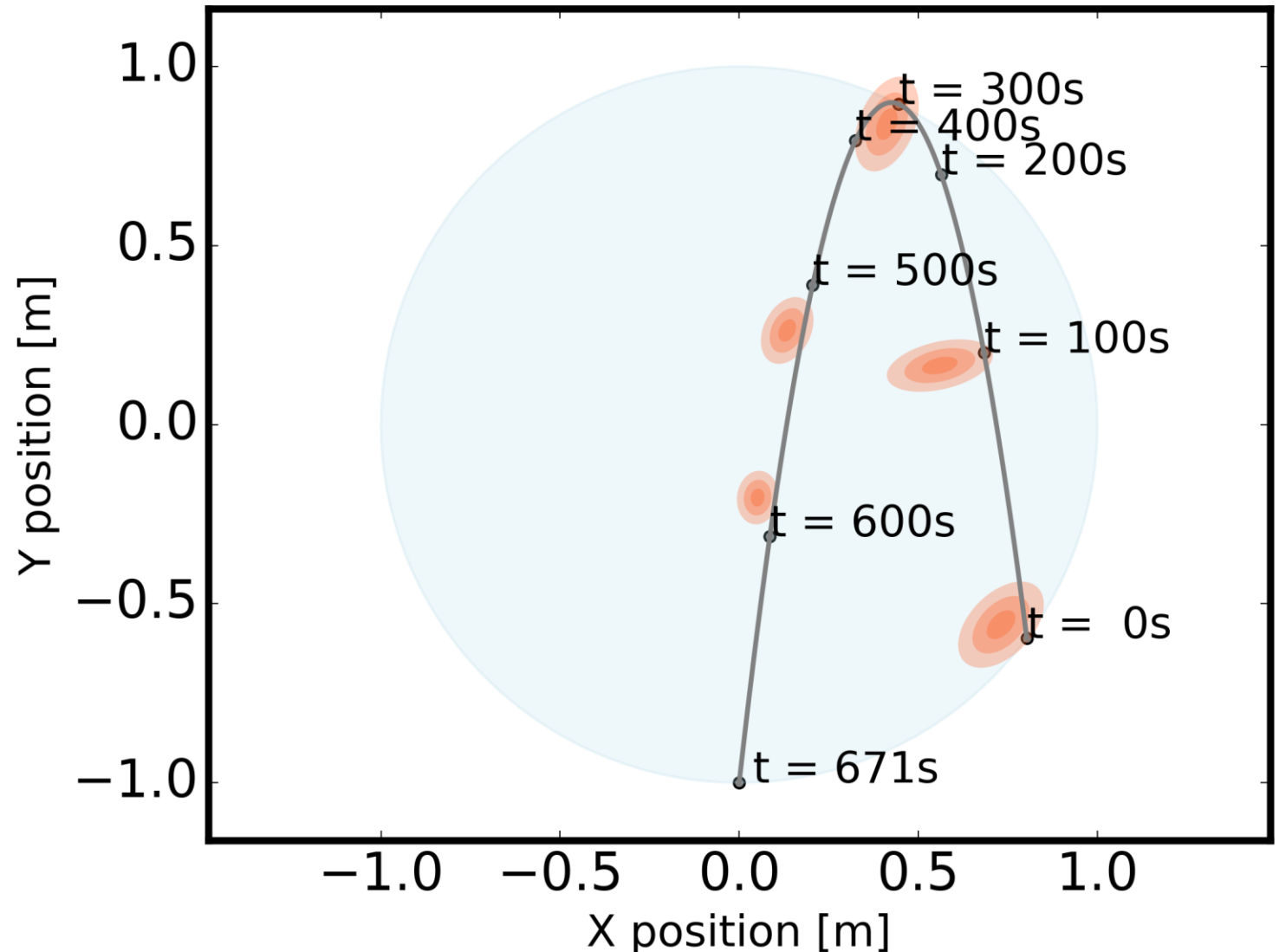


Exoplanet Exploration Program

- **Laser**
 - **20 mW power, uniform**
 - **550 nm**
 - **1.2 degree opening half-angle**
 - Beam profile assumed to be flat
 - Negligible amplitude variation
 - Minor phase sag (incorporated)
- **Camera**
 - readout noise taken from spec sheet (3 - 5 e-/read)
- **Sanity checks through 50% throughput optical system, 500-600 nm, JY21 starshade**

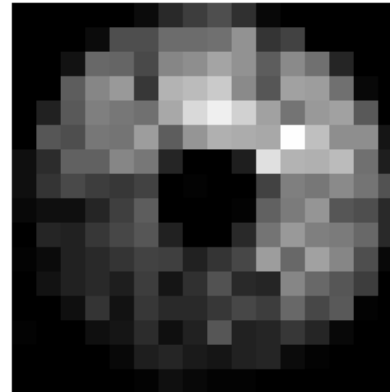
| Star mag | Pre-starshade photons/m2/s | Post starshade photons/m2/s | Laser photons/m2/s |
|----------|----------------------------|-----------------------------|--------------------|
| 3 | 324 e 6 | 174 e 3 | 71 e 3 |
| 4 | 129 e 6 | 69 e 3 | 71 e 3 |
| 5 | 51 e 6 | 27 e 3 | 71 e 3 |
| 6 | 20 e 6 | 11 e 3 | 71 e 3 |
| 7 | 8 e 6 | 4 e 3 | 71 e 3 |

- We basically know where the starshade is
 - Assume ± 7 cm knowledge
- Steps
 - Simulate laser
 - Simulate star
 - Subtract approximate star position
 - Fit remaining data with model of laser tilts

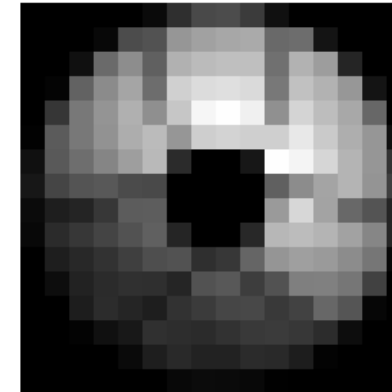


- We basically know where the starshade is
 - Assume ± 7 cm knowledge
- Steps
 - Simulate laser
 - Simulate star
 - Subtract model of approximate star position
 - Fit remaining data with model of laser tilts

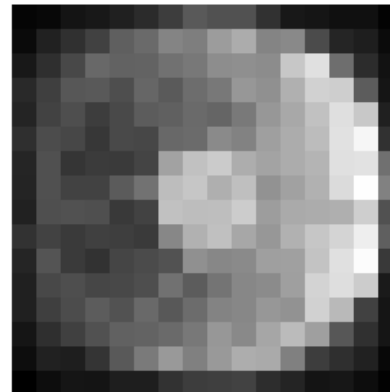
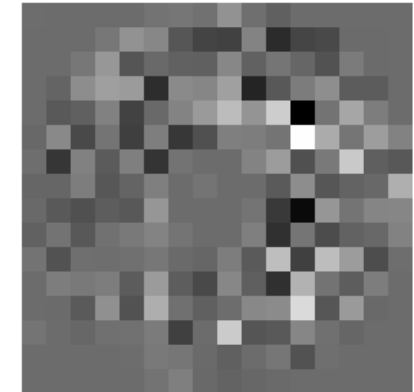
Stellar



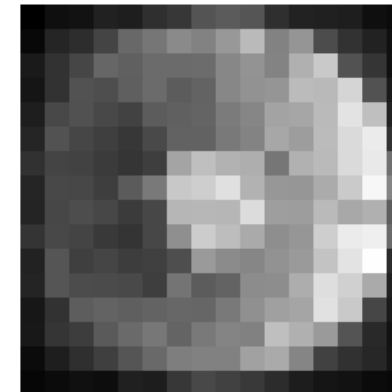
Position



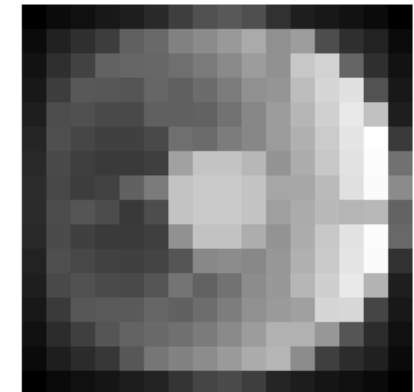
Residual



Laser photons



Laser +
Residual



Match

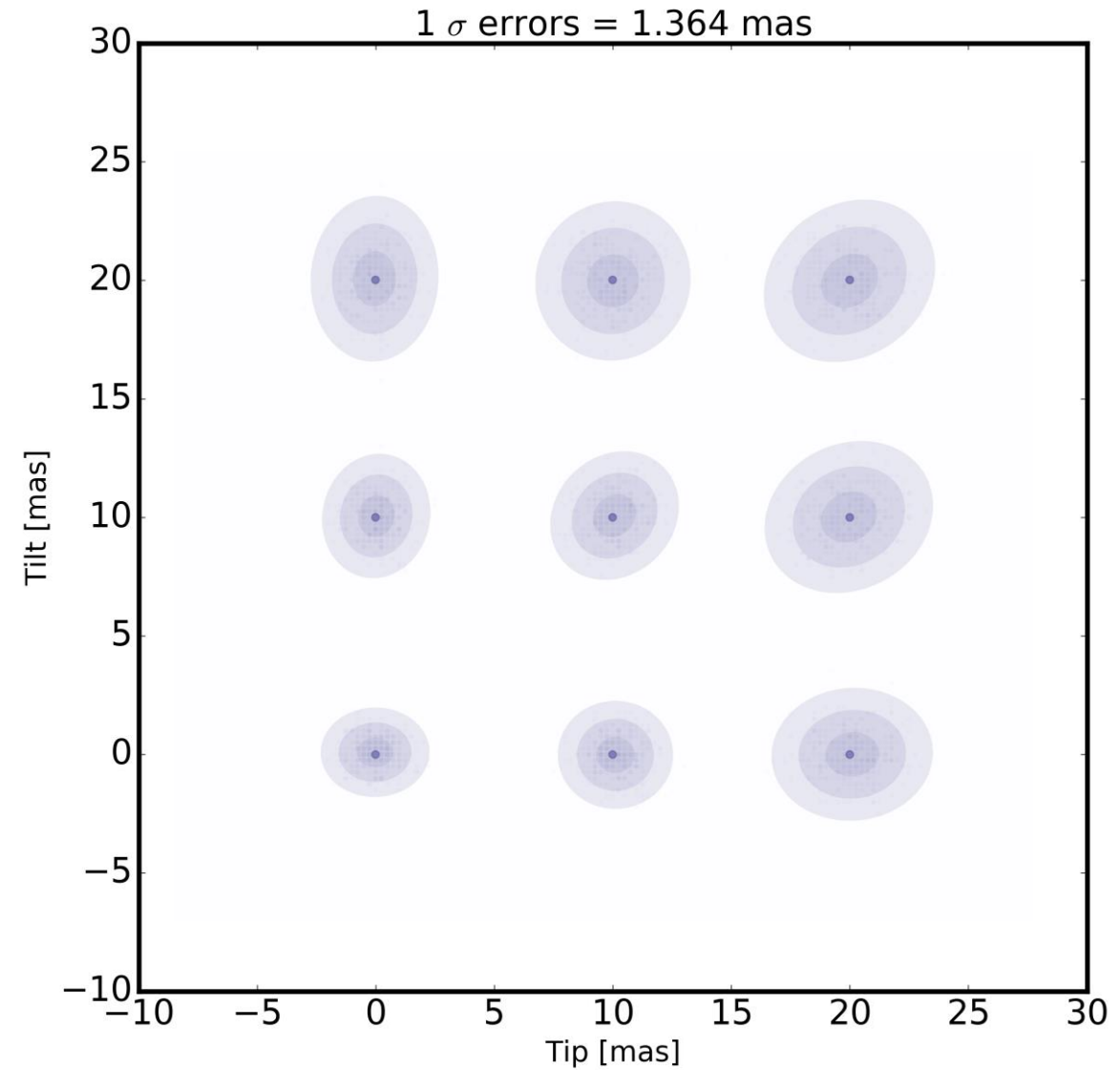


Red science band (550 nm laser)



Exoplanet Exploration Program

- 1 ms read time
- **0.5 Watt laser**
- 1st magnitude star



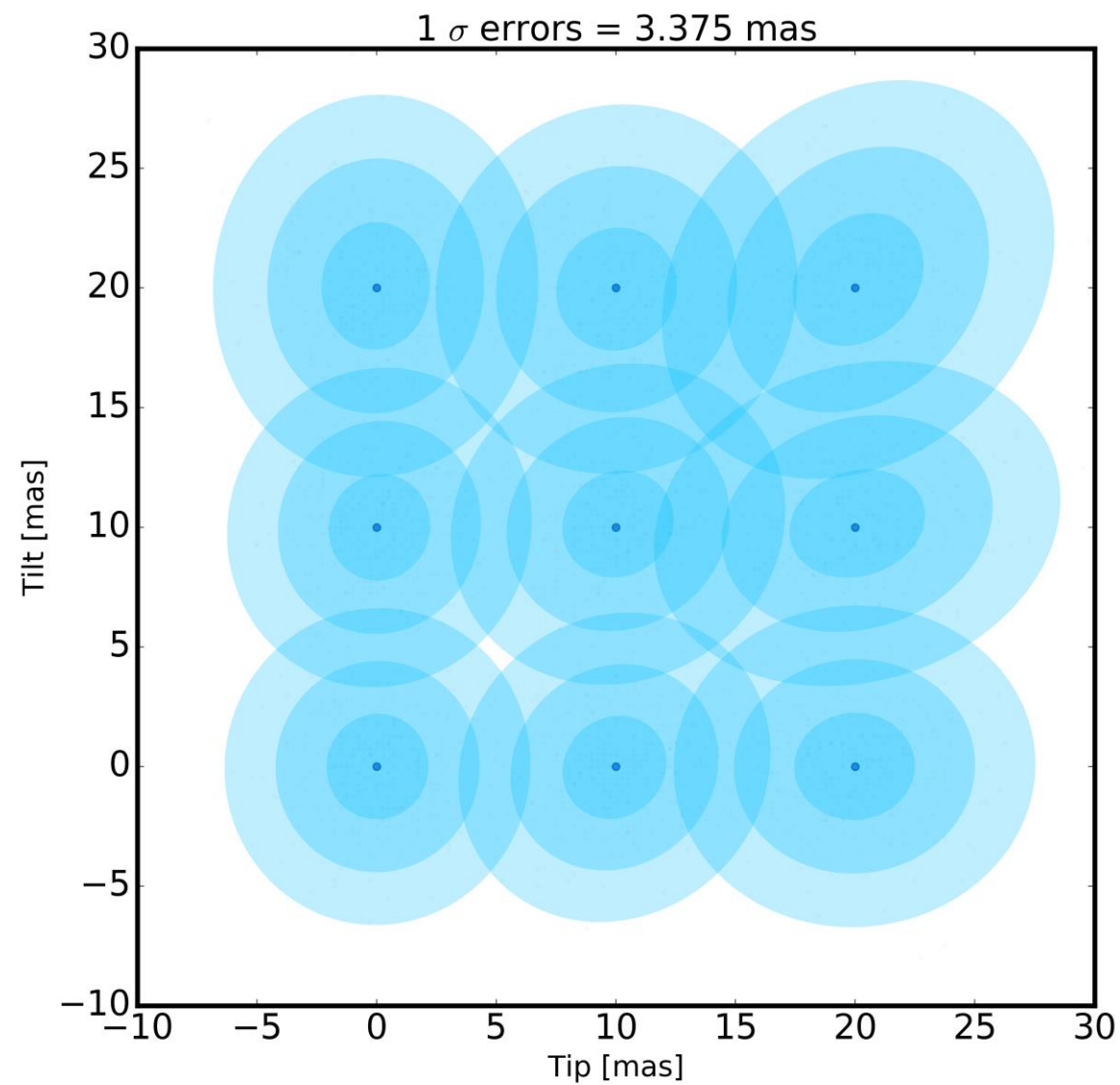


Blue science band (950 nm laser)



Exoplanet Exploration Program

- 1 ms read time
- **2 Watt laser**
- 1st magnitude star





Summary



Exoplanet Exploration Program

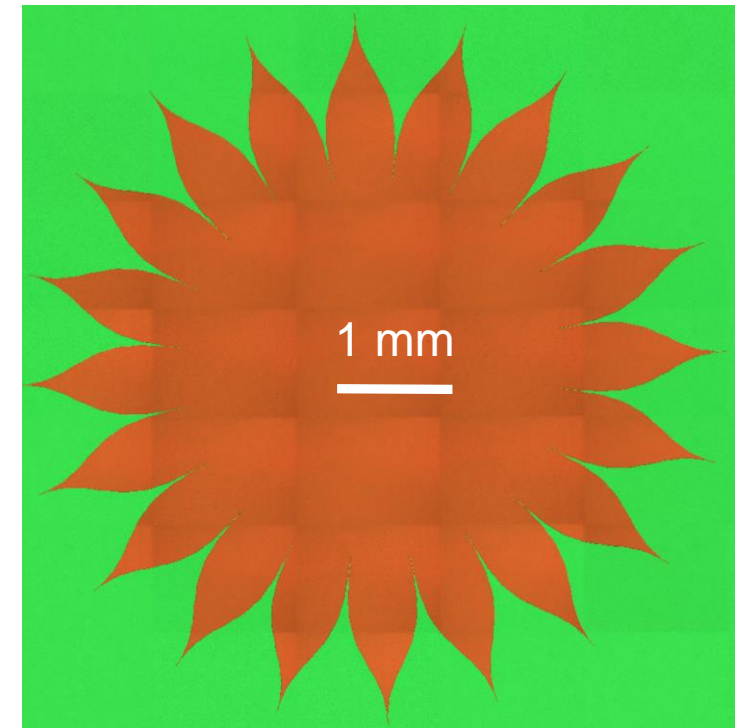
| | Laser power for <1 mas, 1 st mag star bgd, Position known | Laser power for < 1mas, 1 st mag star background, No position info | Laser power for <3 mas, 1 st mag star bgd, Position known | Laser power for <3 mas, 1 st mag star bgd, No position info |
|----------------------------|--|--|--|--|
| Red Science band (550) | 0.5-2 Watts | 5 Watts | 0.25-0.5 Watts | 2 Watts |
| Blue Science band (950) | 10 Watts | 20 Watts | 2 Watts | 5 Watts |

- 20 mW laser massively underpowered for tip/tilt sensing
- Using position info, sense to 1 mas with 2 Watts (red) and 10 Watts (blue)
- With no position info, can use 5 Watts (red) and 20 Watts (blue)



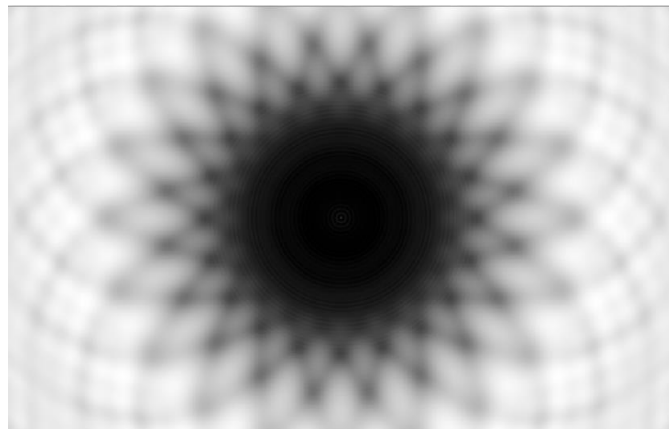
Not to scale

- Goal: reproduce guiding signal, eventual closed-loop guiding control
- Starshade and WFIRST pupil masks fabricated and mounted.
- Motorized stages to simulate guiding trajectory corrections
- Numerical simulation of lab demo
 - OK agreement so far
- Challenge: still too much diffraction from optical mounts

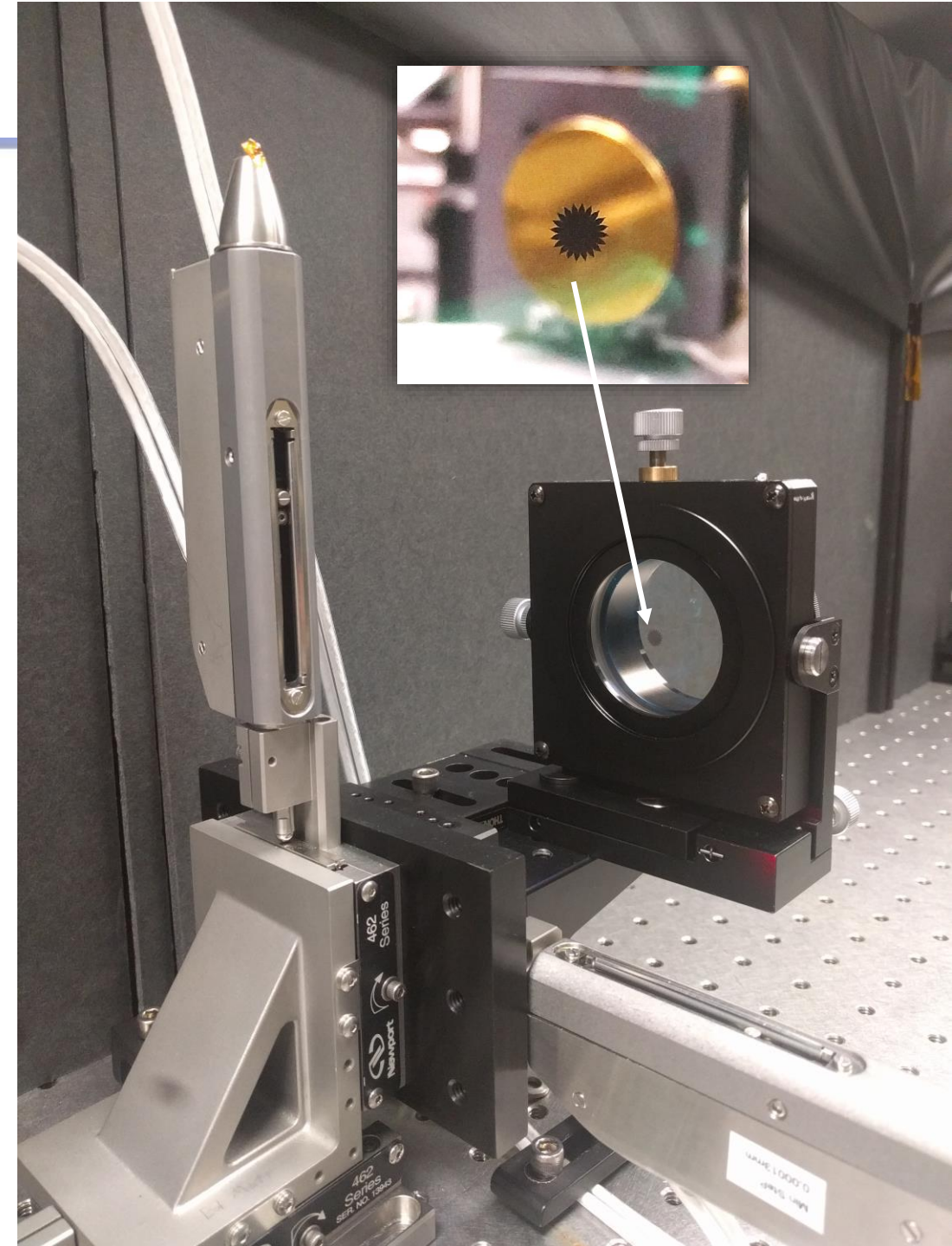
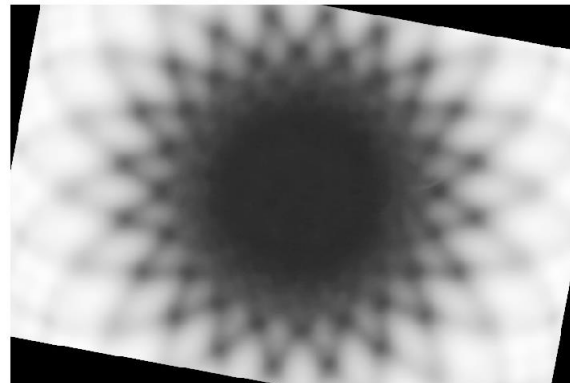


- Goal: reproduce guiding signal, eventual closed-loop guiding control
- Starshade and WFIRST pupil masks fabricated and mounted.
- Motorized stages to simulate guiding trajectory corrections
- Numerical simulation of lab demo
 - Good agreement so far
- Challenge: still too much diffraction from optical mounts

Fresnel simulation of lab starshade



Lab starshade data (same scale)





Conclusions



Exoplanet Exploration Program

- Plenty of stellar photons to
 - Correct shear in the dark zone for science observations
 - Correct slow drifts in tip and tilt
 - Initially acquire the dark zone from
- ~Watt class lasers required to correct fast tip/tilt jitter
 - But even if you don't, probably OK
- Lab experiments underway to test and validate these simulations

Thanks!! Questions?

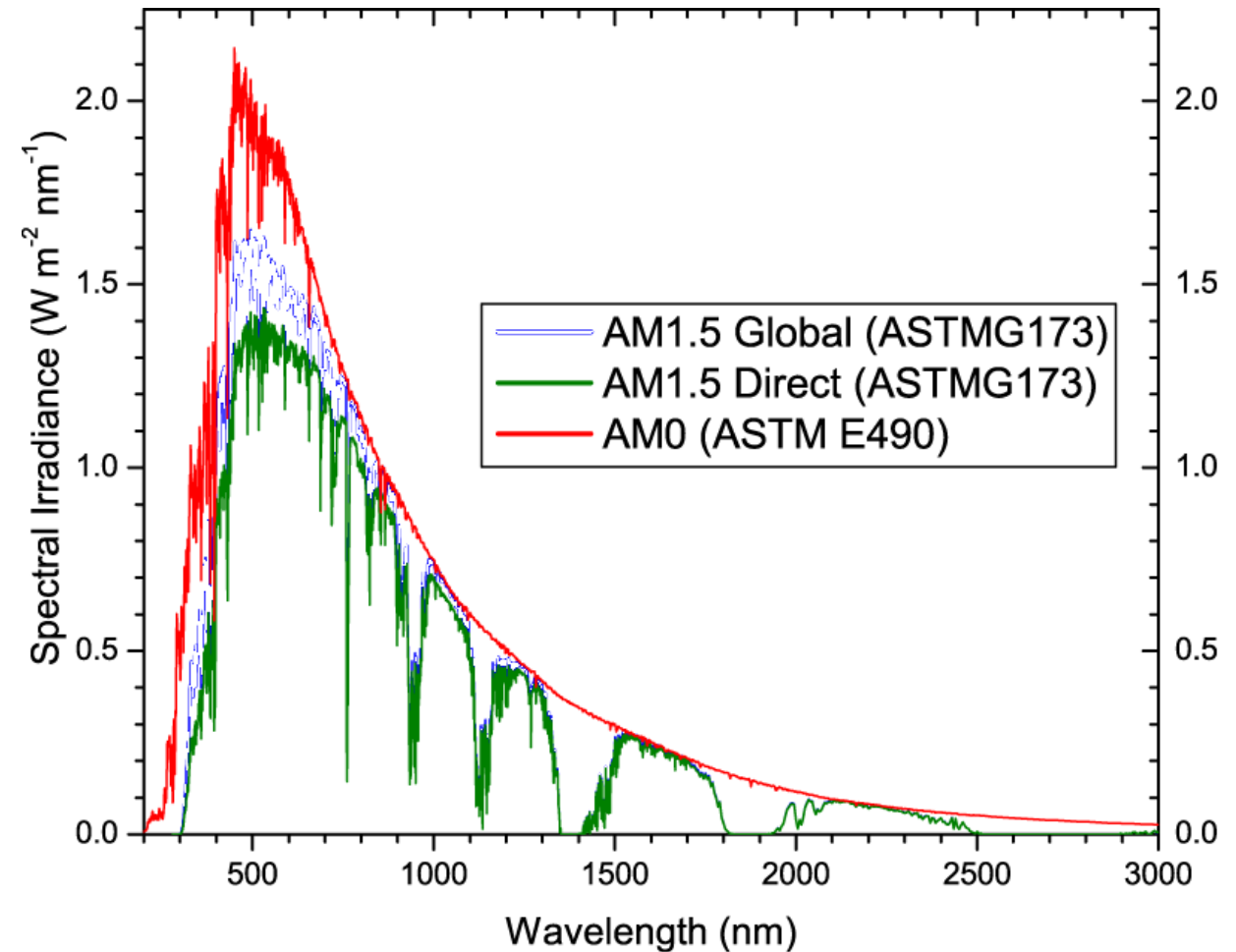


Extra slides



Exoplanet Exploration Program

- ATLAS9 synthetic spectral atlas
- Sun-like star
 - $T_{\text{eff}} = 5750$
 - $\log g = 0.0$
 - $[\text{Fe}/\text{H}]$ (metal content) = 0
- Also:
 - Solar radius + distance
 - Magnitude (conversion)
- Checked power and photons/s using photometric zeropoints of stars, solar spectrum @Earth, excellent agreement



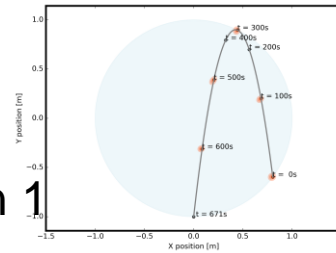


Effects of jitter are very minor



Exoplanet Exploration Program

No jitter, **2 cm** 1-sigma precision in **1** second

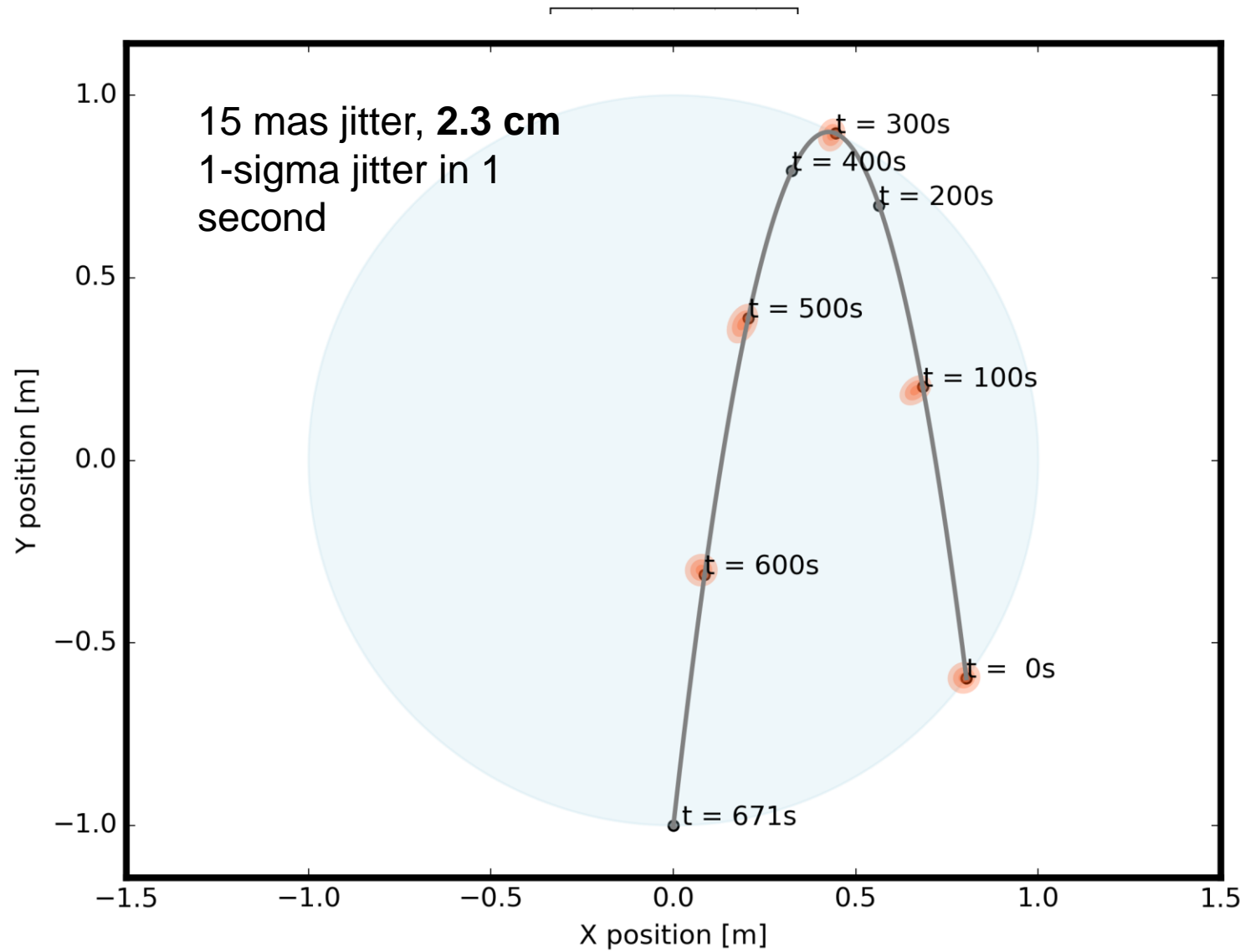




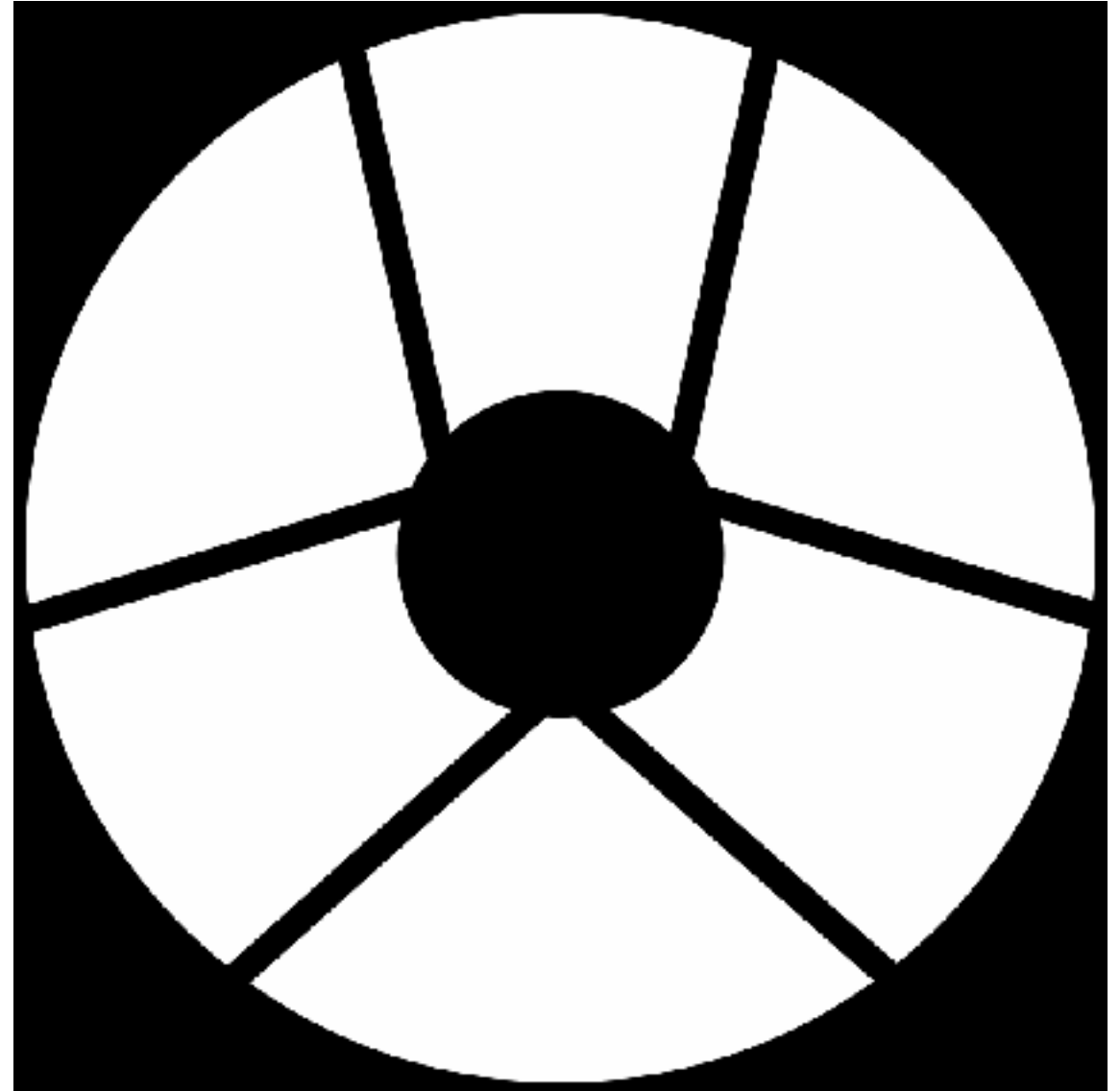
Effects of jitter are very minor



Exoplanet Exploration Program

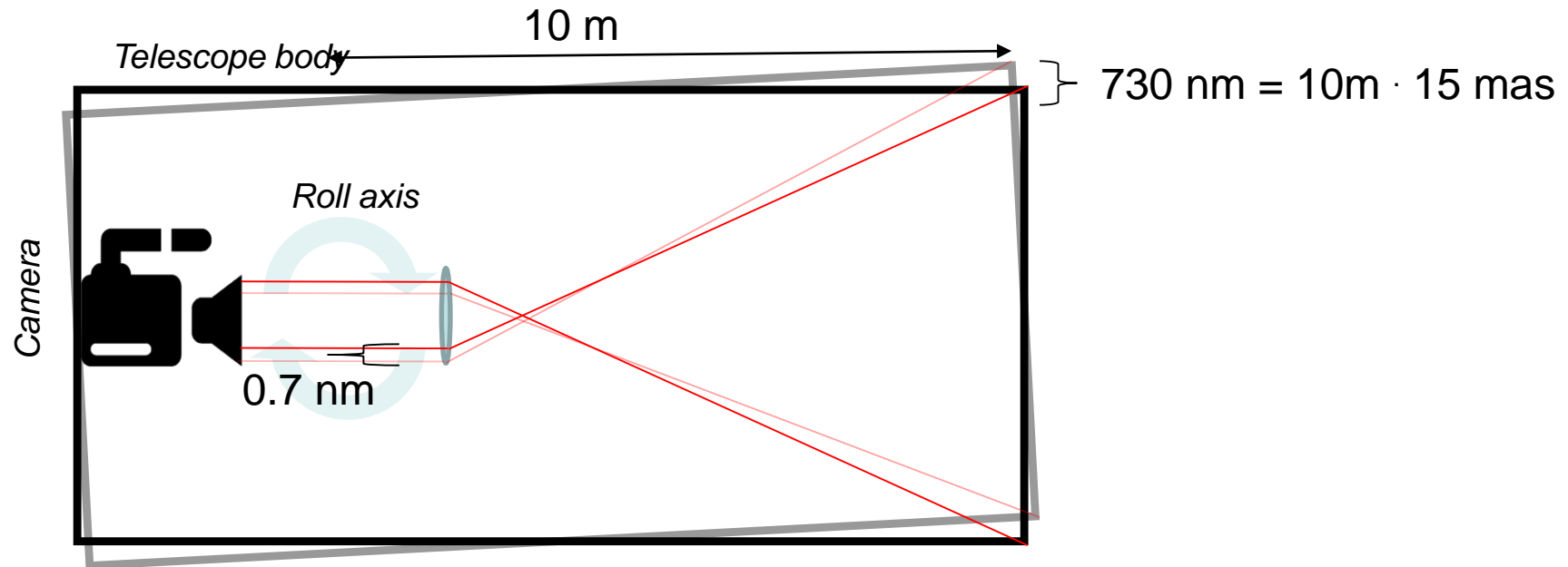


- From J. Krist
- Binary mask
- 2 mm/pix resolution

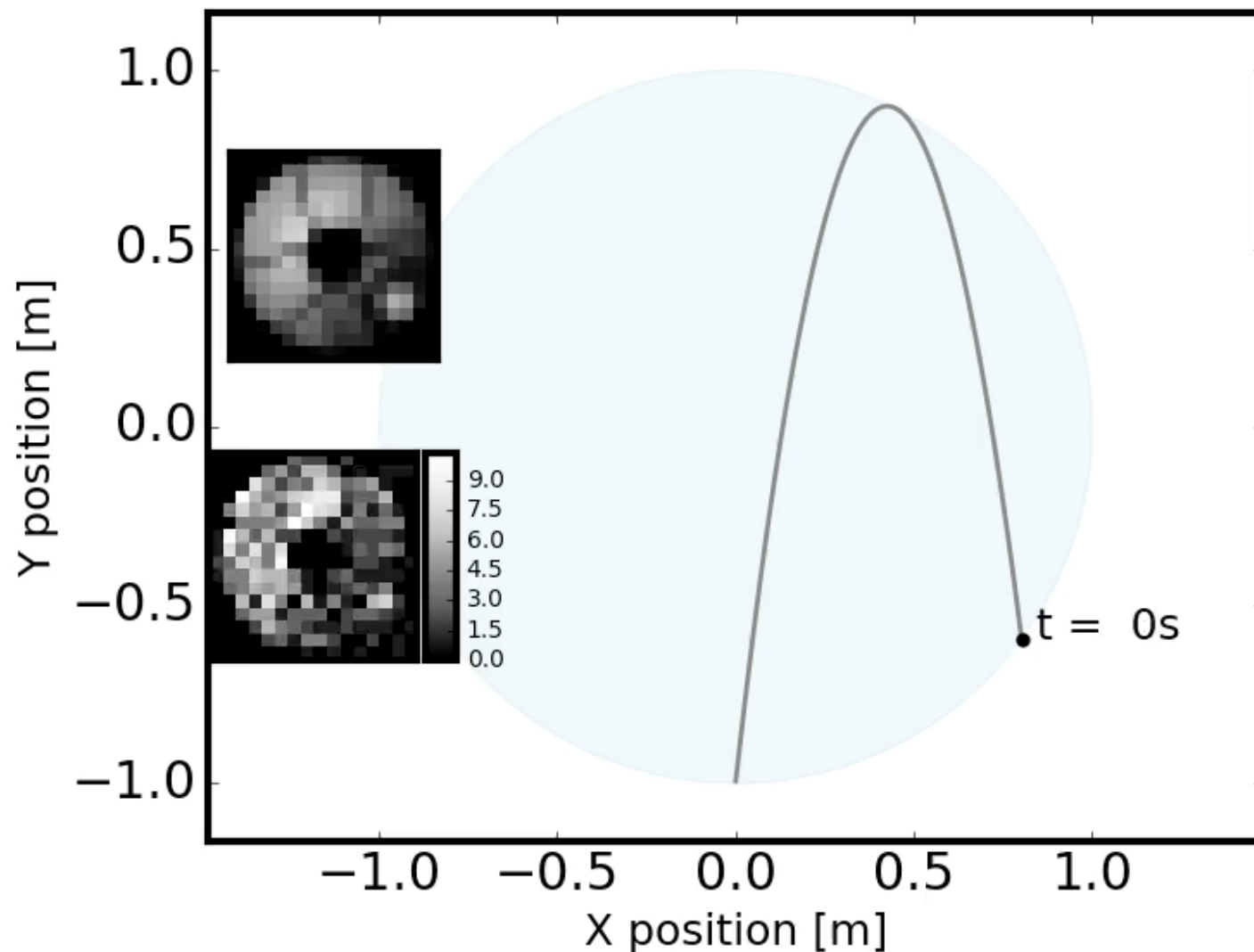


Why jitter is not relevant for shear sensing

- 15 mas jitter \rightarrow 730 nm of pupil motion (at telescope input)
- Magnification factor = $2.4 \text{ m} / 0.002 \text{ mm}$ detector size ~ 1000
- Motion on pupil camera = $730 \text{ nm} / 1000 = 0.7 \text{ nm} = 3\text{e-}5 \text{ pixels} =$ negligible

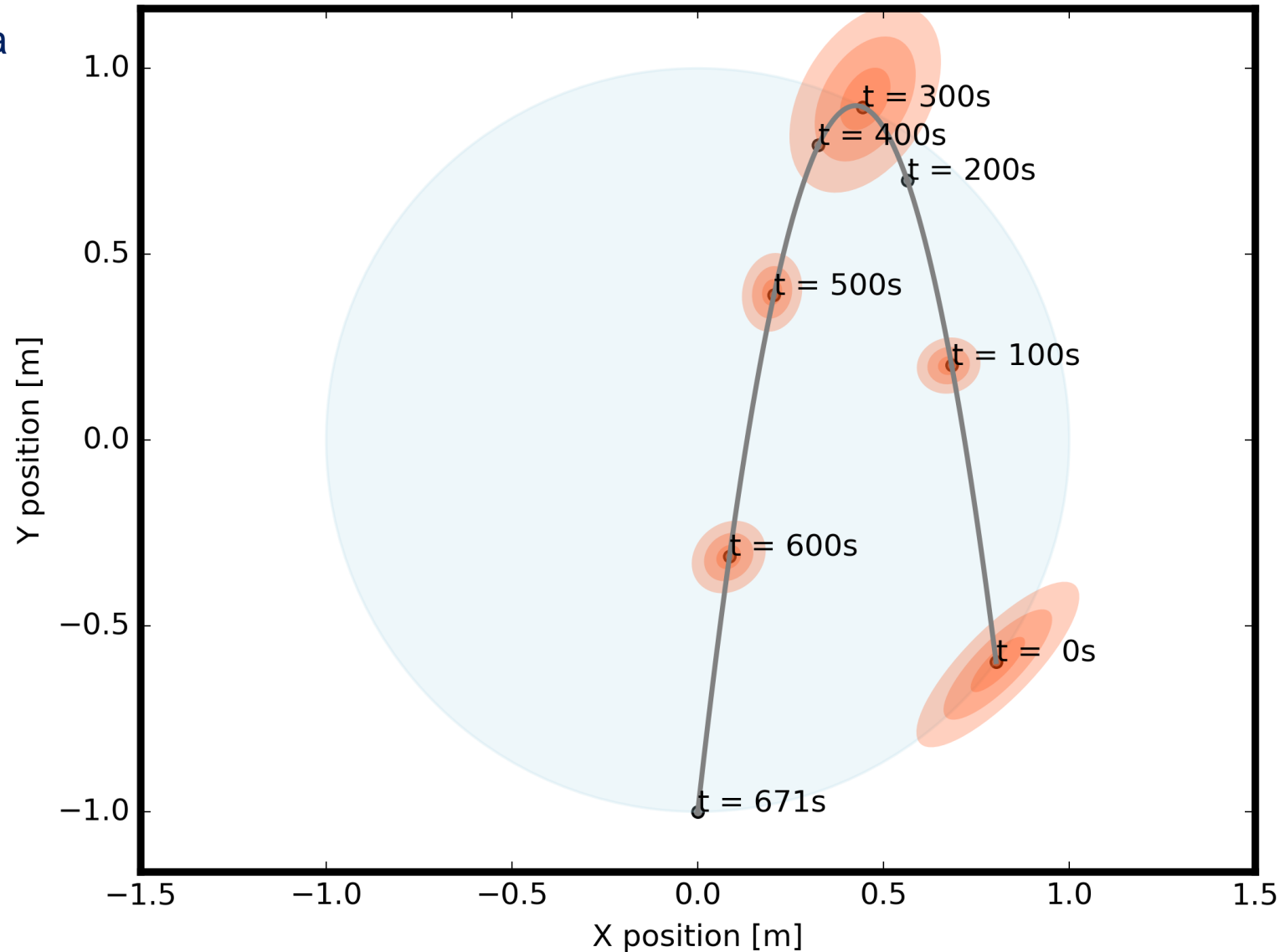


- Generate 1000 1s noisy images at a trajectory point
- Match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → save shear positions
- Get mean and std.dev of different shear positions





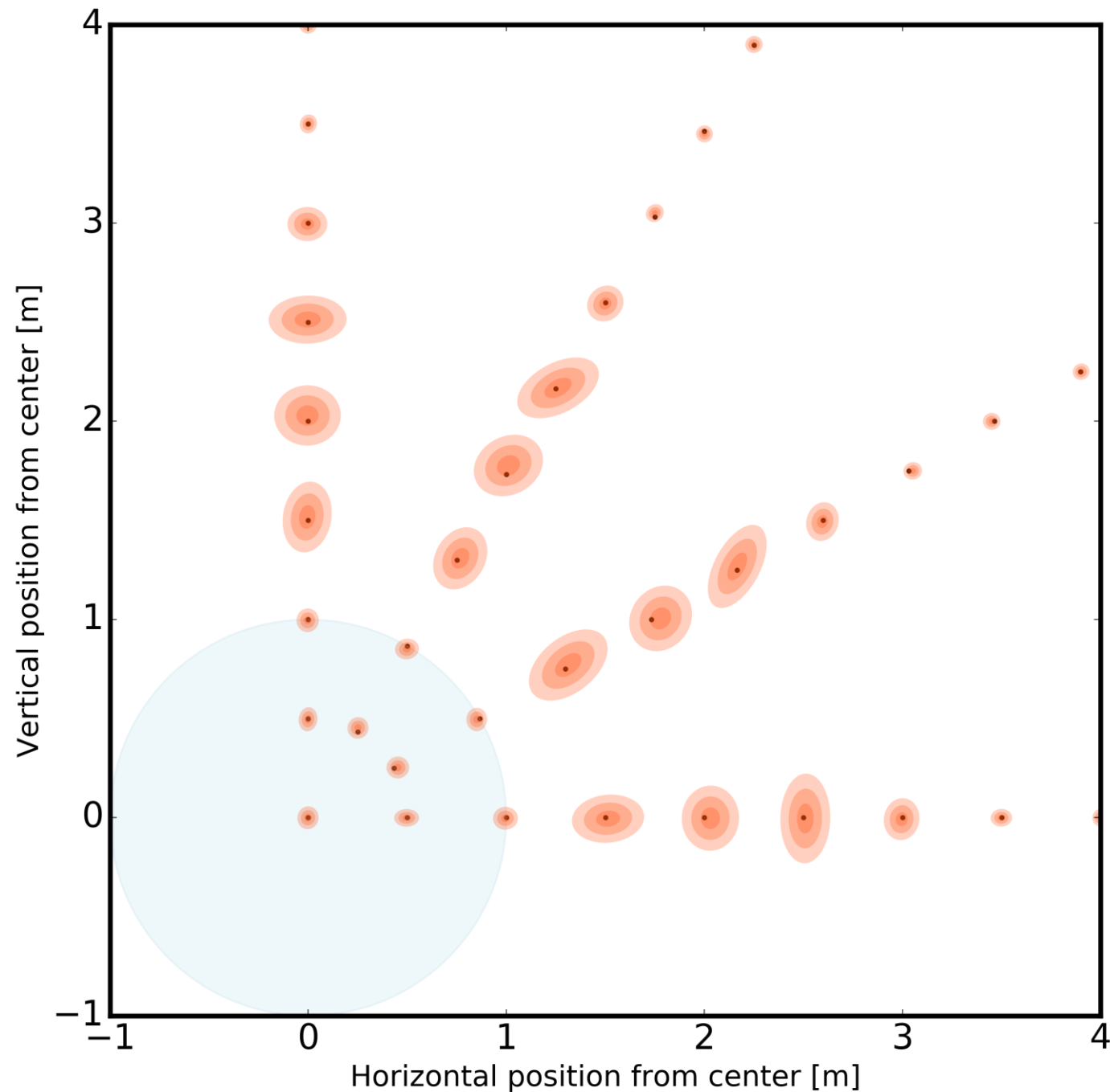
- Generate 100 1s noisy images at a trajectory point
- match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → corresponding shear position
- Get mean and std.dev of different shear positions

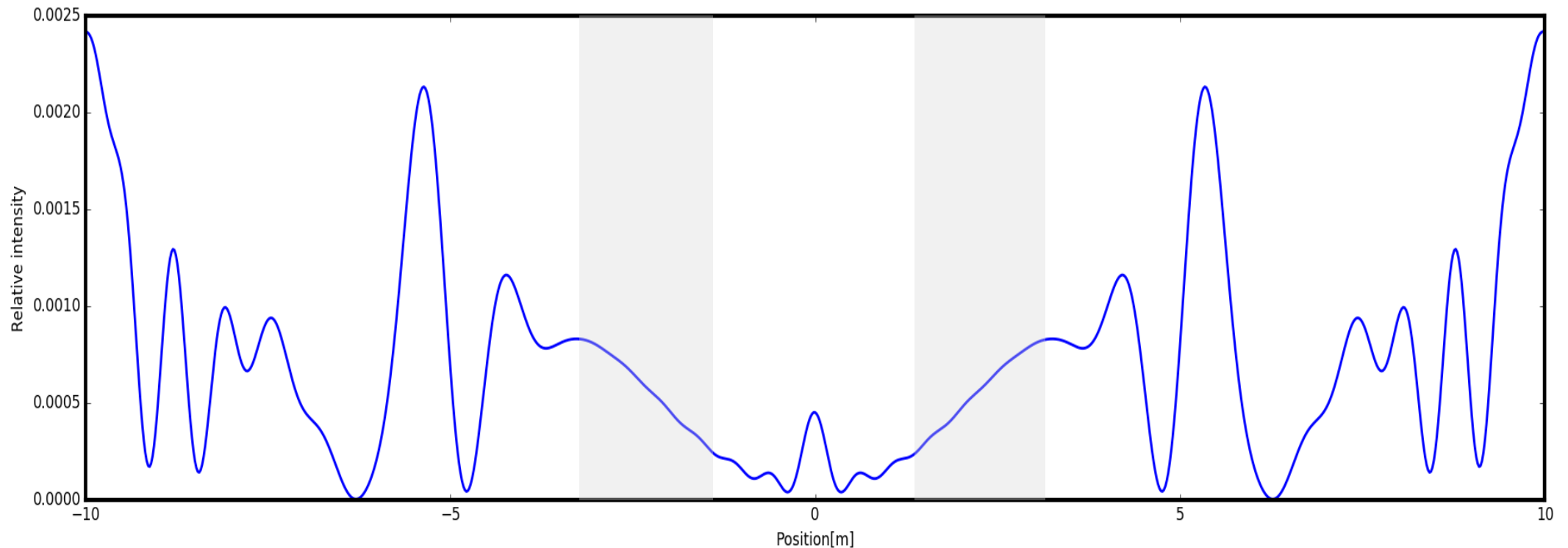




LOWFS signal, 8th magnitude star

- Generate 400 1s noisy images at different radial positions
- match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → corresponding shear position
- Get mean and std.dev of different shear positions



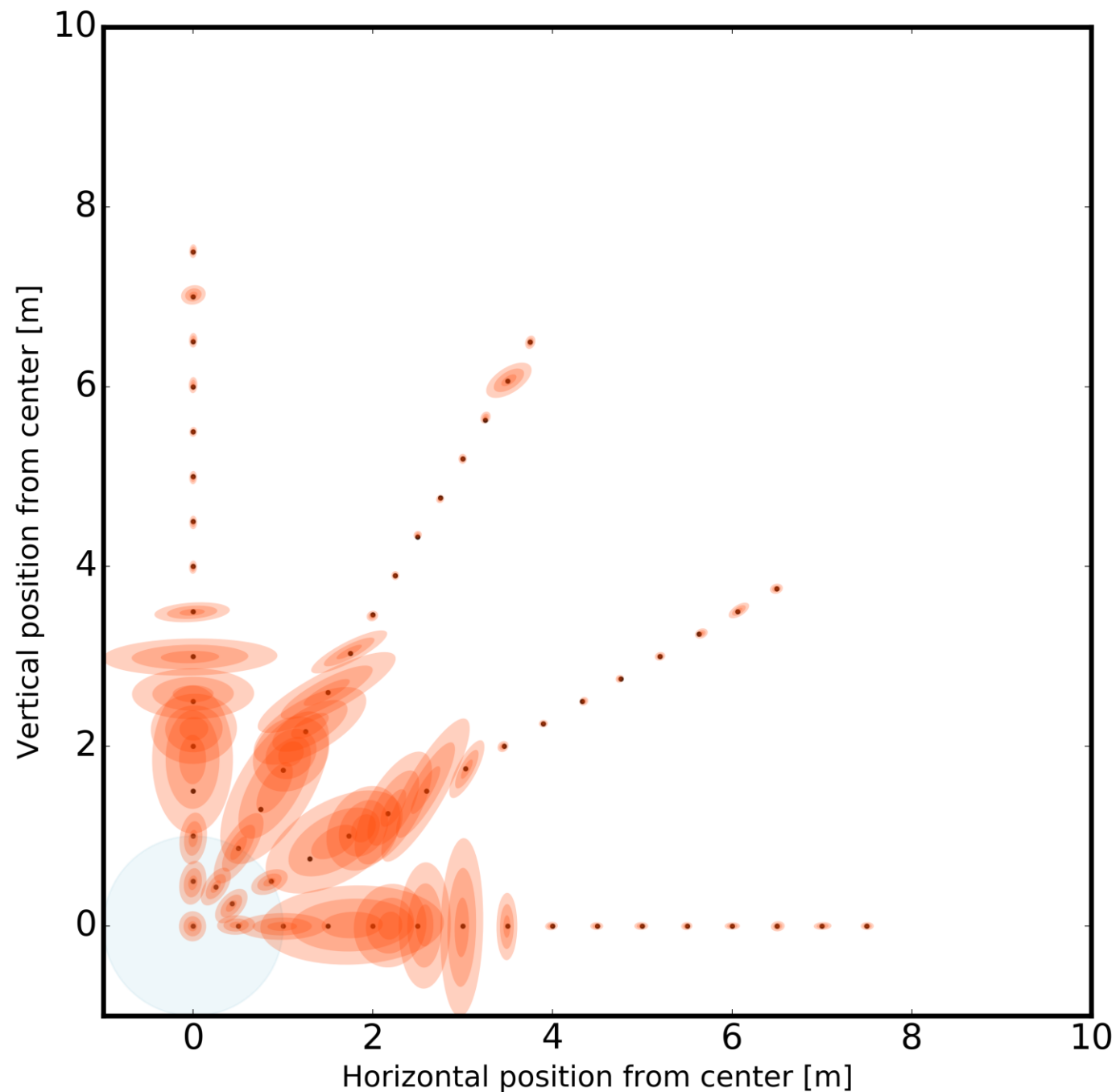


- Areas of lower relative precision correspond to constant gradient
- This is due to the matched filter operating on relative flux levels
- In practice follow the gradient to the center



LOWFS signal, 10th magnitude star

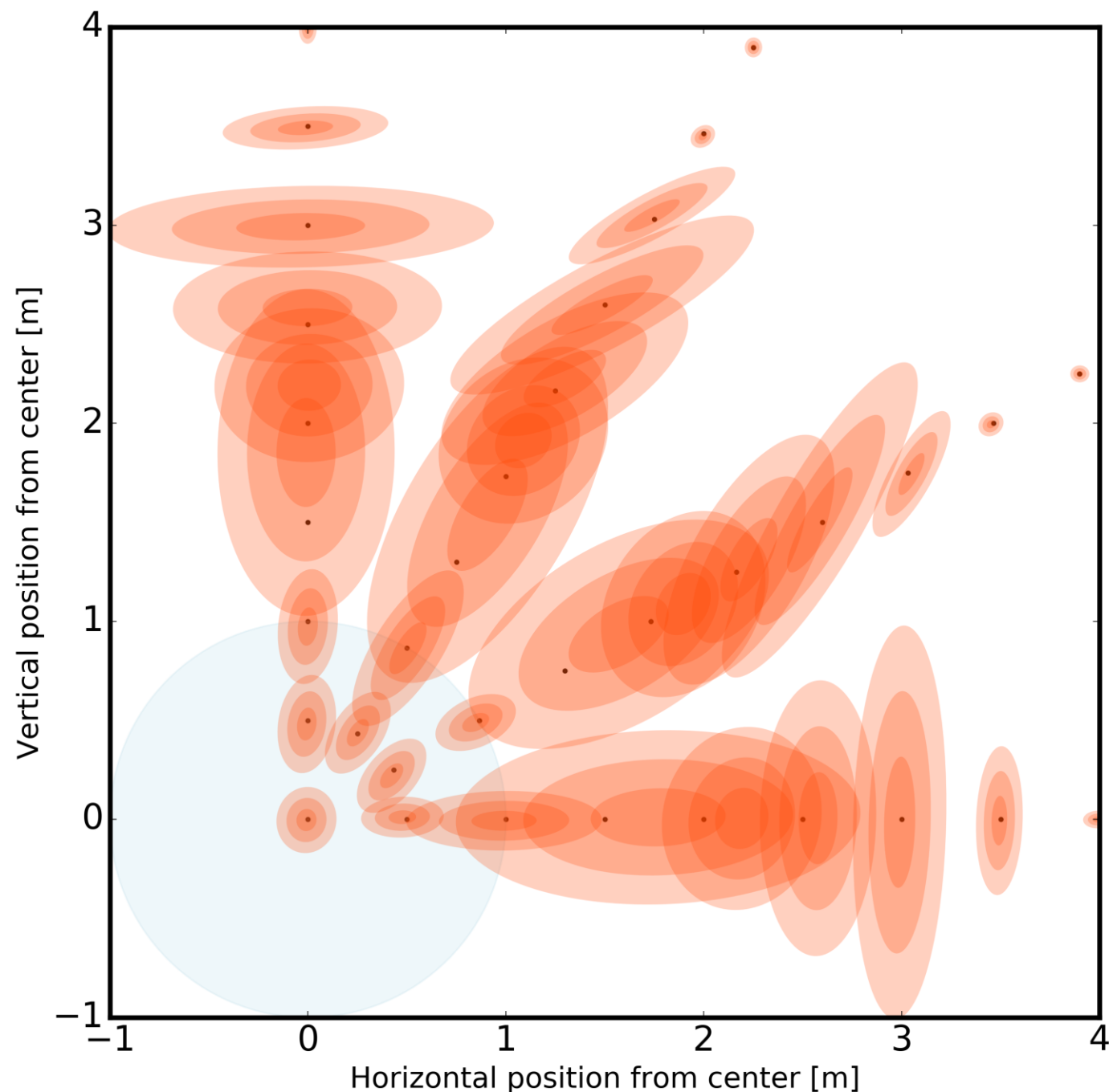
- Generate 400 1s noisy images at different radial positions
- match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → corresponding shear position
- Get mean and std.dev of different shear positions





LOWFS signal, 10th magnitude star

- Generate 400 1s noisy images at different radial positions
- match each noisy image to library of ~50000 clean images @ 2cm grid resolution (matched filter)
- Find closest match → corresponding shear position
- Get mean and std.dev of different shear positions



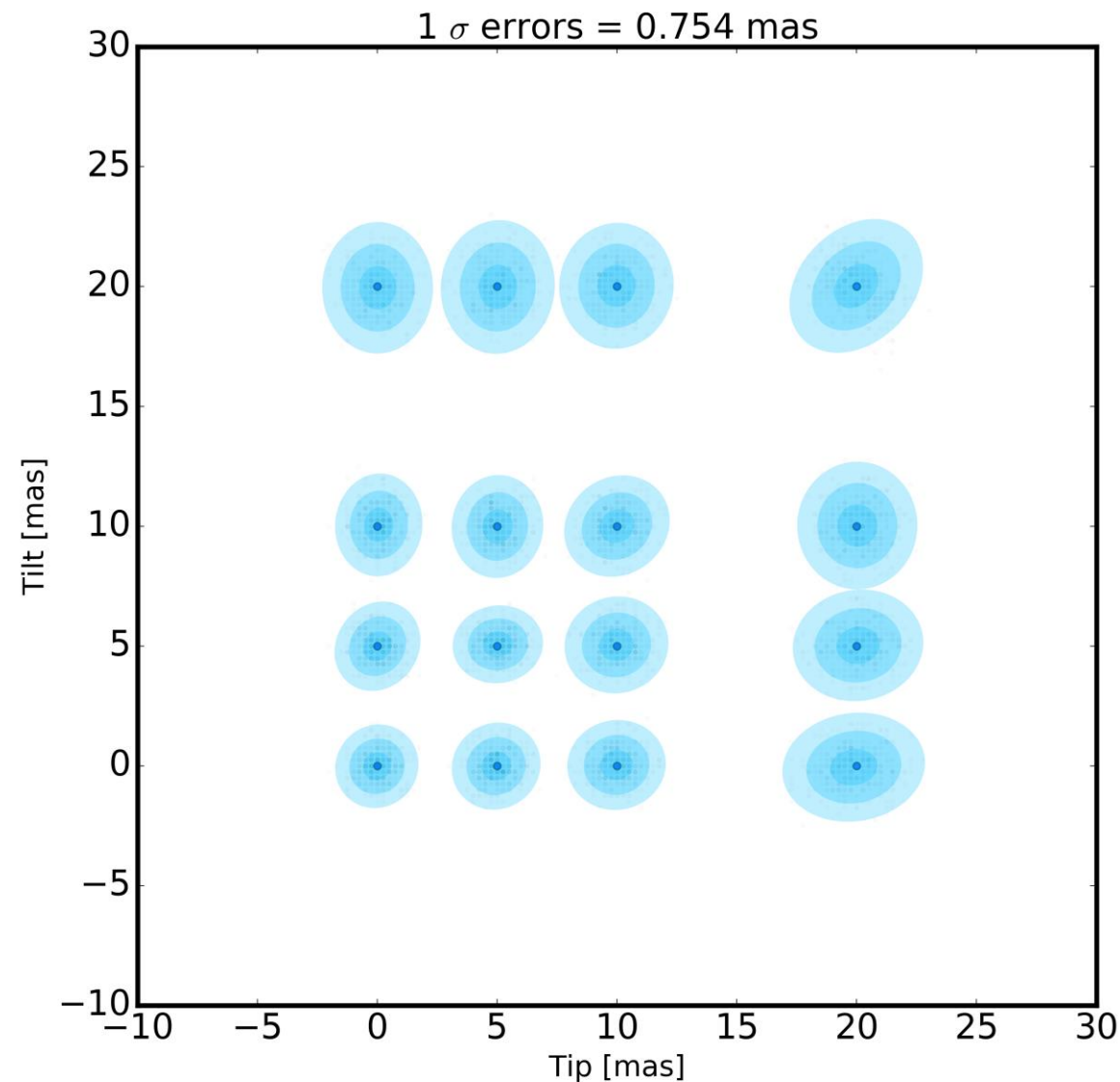


Laser only, no stellar shear signal

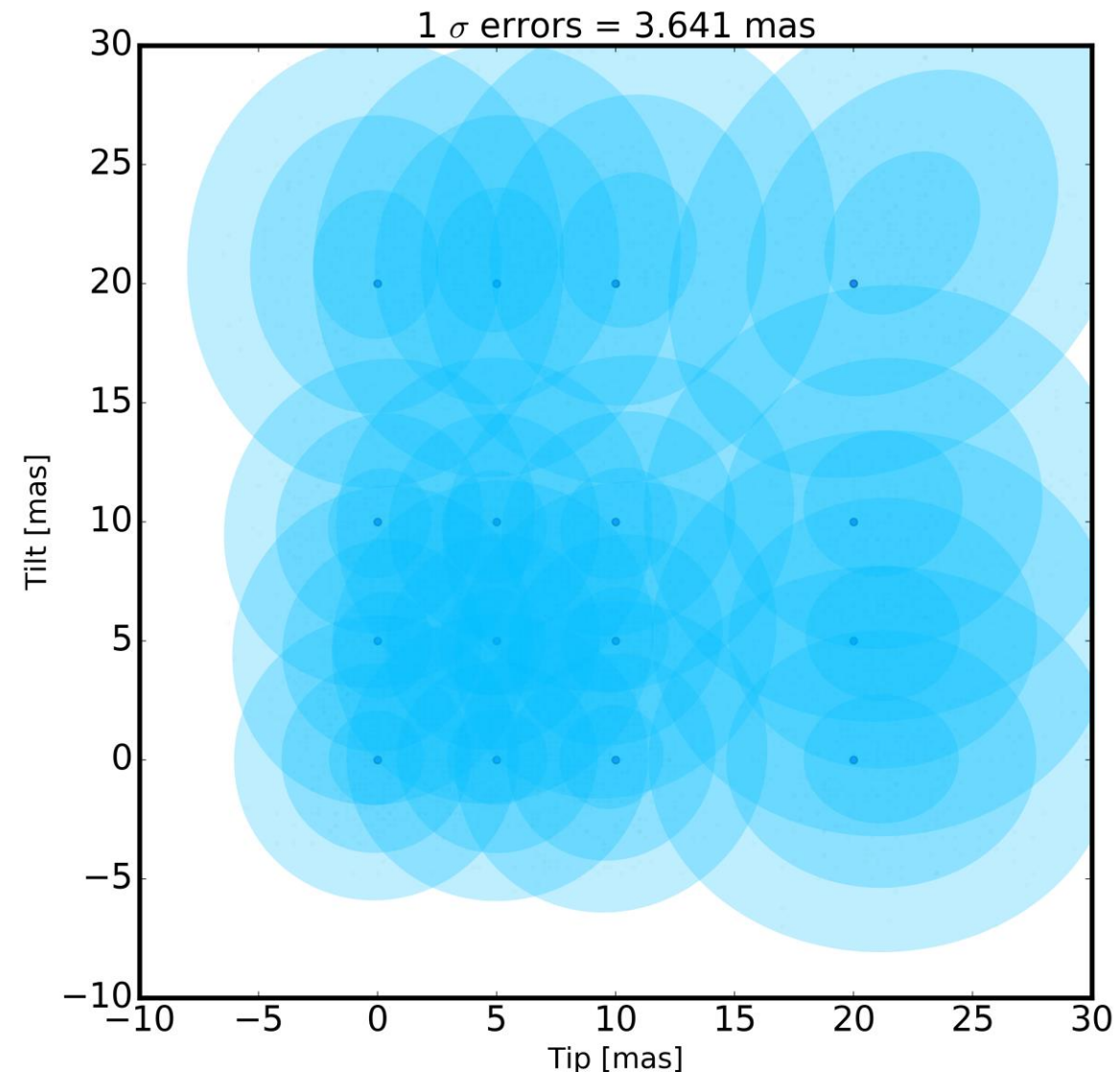


Exoplanet Exploration Program

- **0.03 s exposure time**
 - Or! 60 mW laser w/0.01 s exptime
 - 5 e- read noise
- Get 0.75 mas 1 sigma precision
 - good enough?
- Corrects ~5Hz errors
- Read noise limited



- Methodology: add two noisy camera frames, laser and star, then solve using a matched filter on **only** the laser frames
- **0.01 s exposure time**
 - 5 e- read noise
- **6th magnitude star**
- **Random shear signal inserted at each iteration**
- Note errors ~2x larger



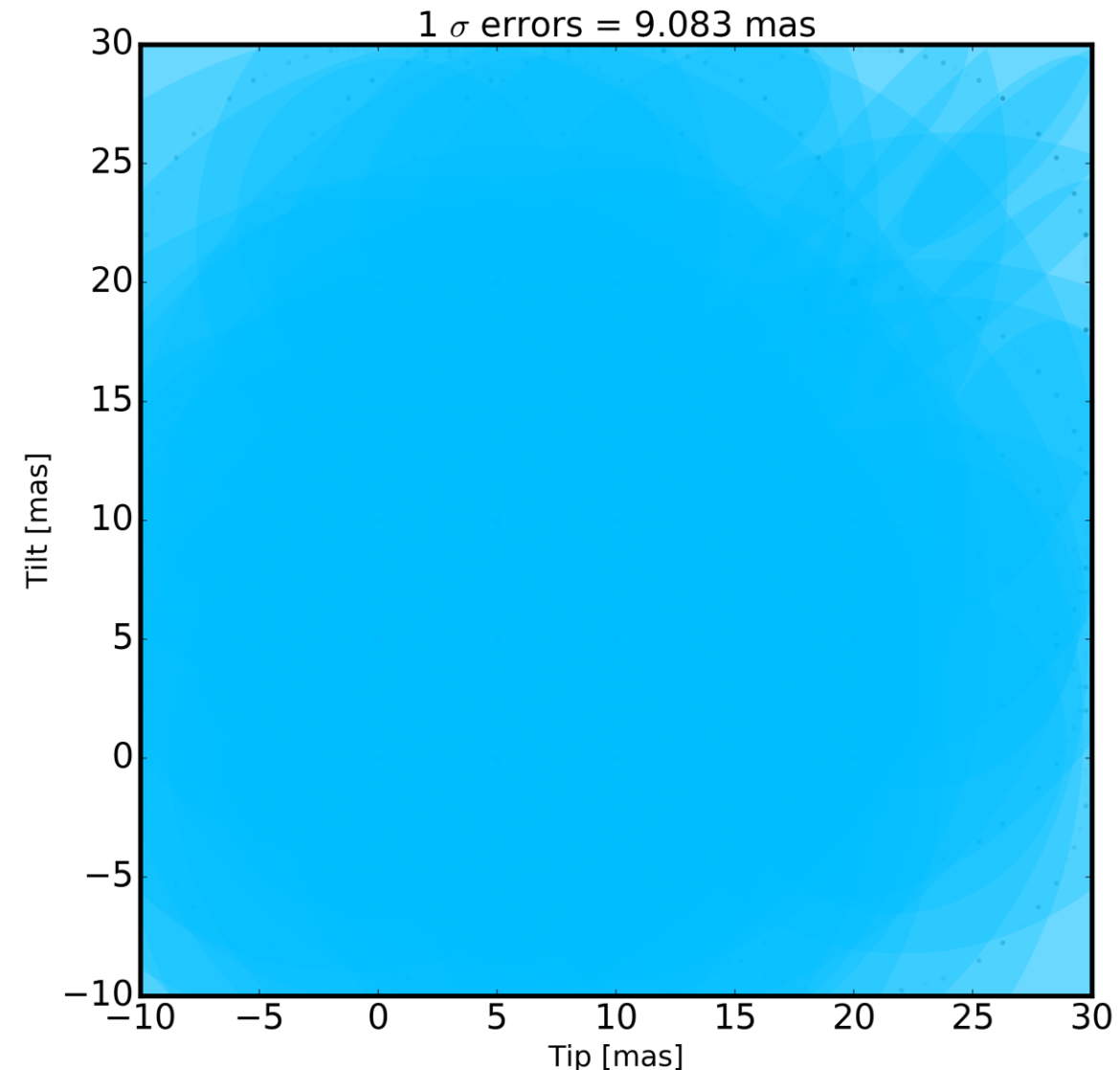


Laser *with* random stellar shear signal



Exoplanet Exploration Program

- Methodology: add two noisy camera frames, laser and star, then solve using a matched filter on **only** the laser frames
- **0.01 s exposure time**
 - 5 e- read noise
- **3rd magnitude star**
- **Random shear signal inserted at each iteration**
- Useless (railed)





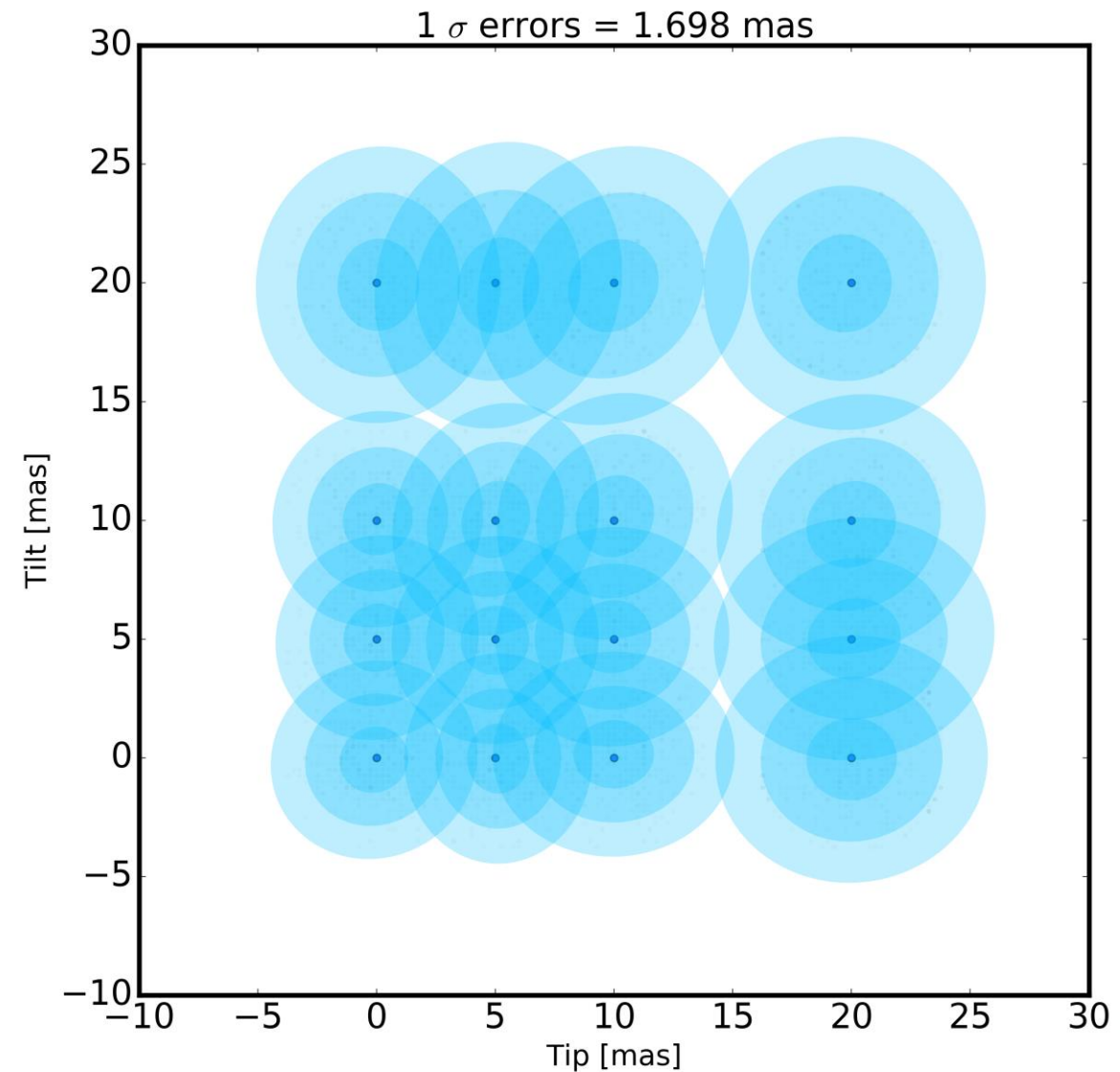
Methodology



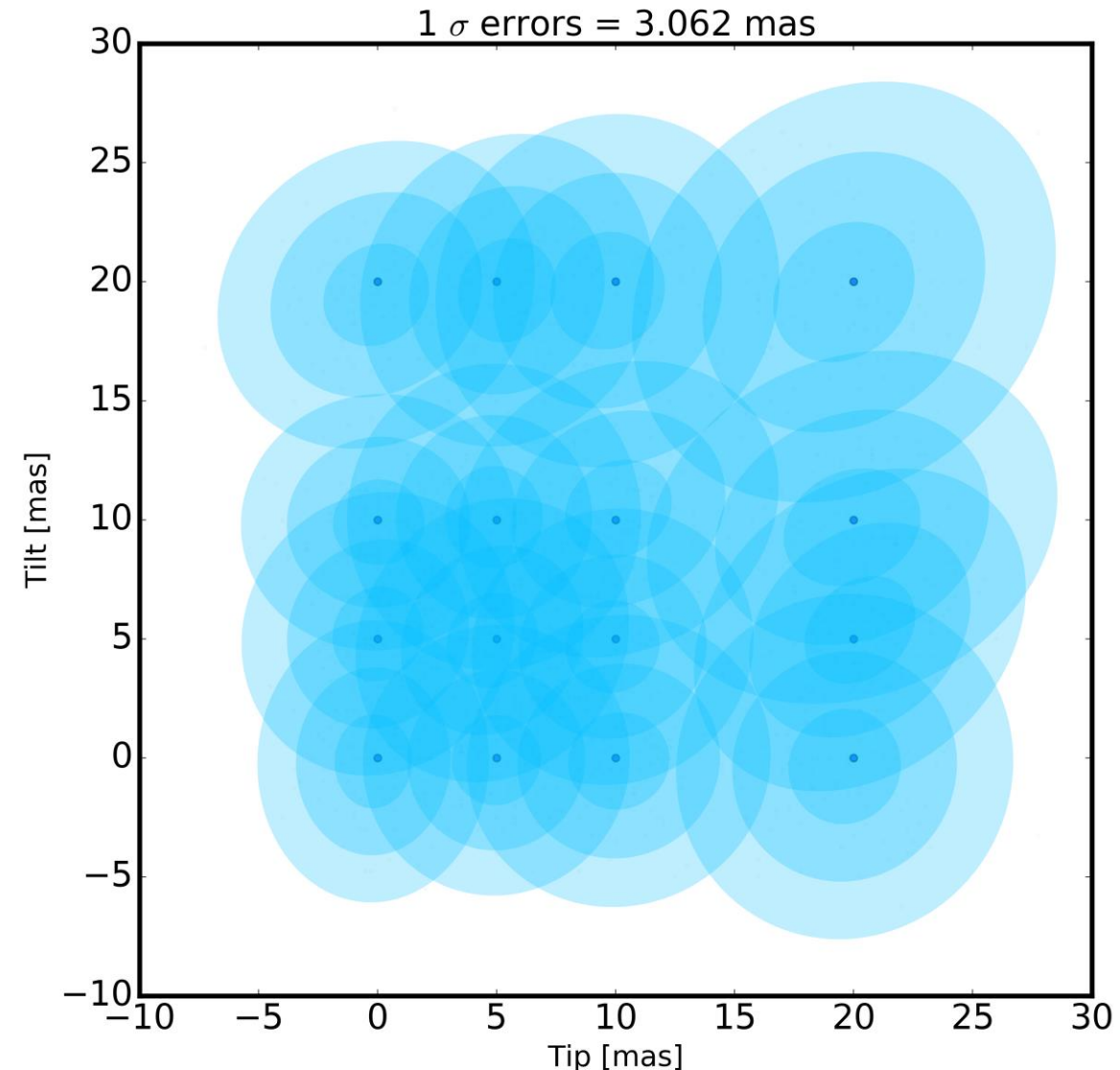
Exoplanet Exploration Program

- Simulate 60000 tip/tilt offsets
 - -30 – 30 mas
 - 0.25 mas resolution
- Simulate camera image
 - Add read noise
 - Add shot noise
- Use matched filter to recover tip/tilt
- Do this 400x/pt
 - Get mean, std deviation

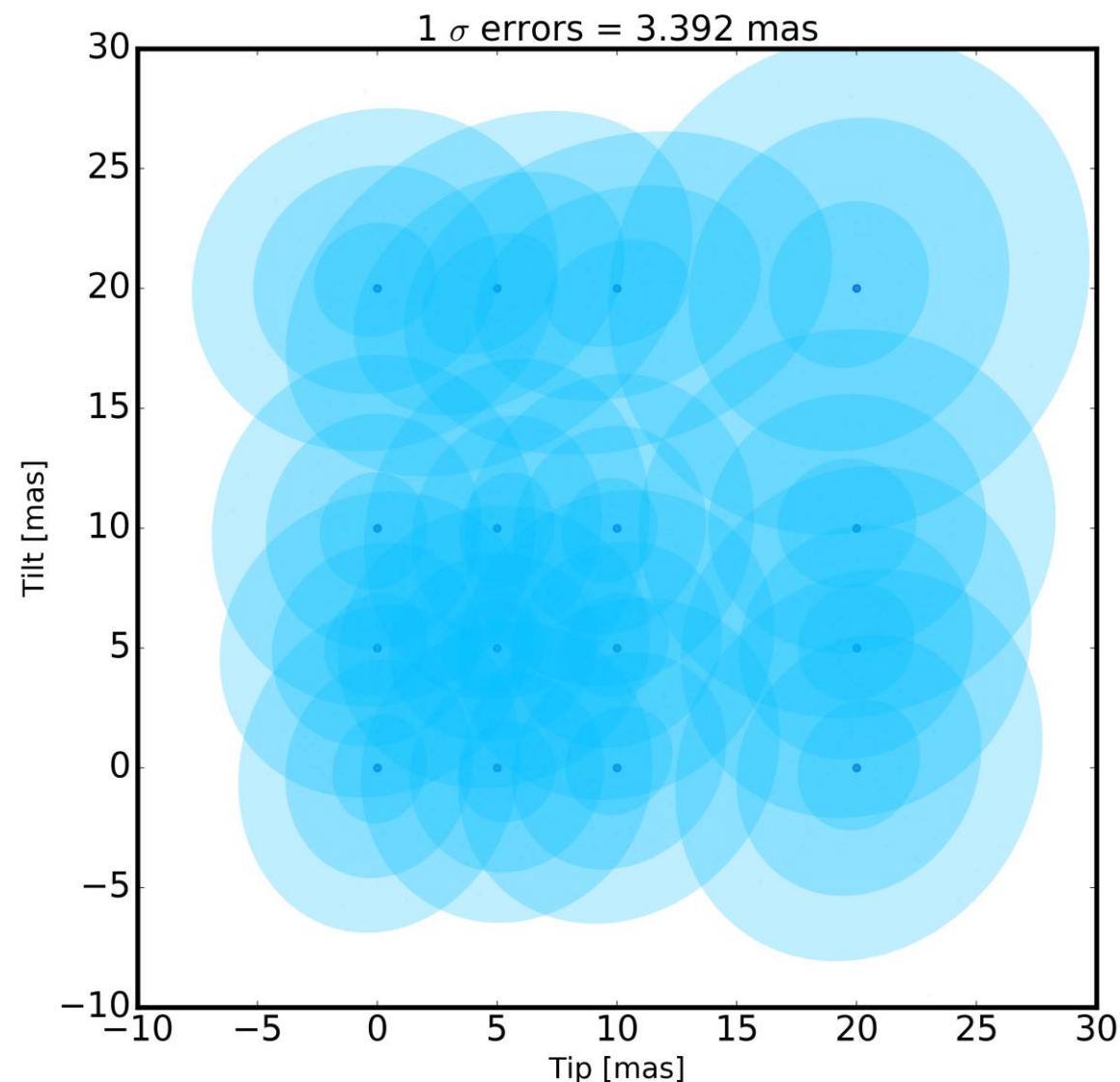
- **0.01 s exposure time**
 - 5 e- read noise
- Get 1.7 mas 1 sigma precision
 - good enough?
- Corrects ~10Hz errors
- **The 20 mW laser is too faint**



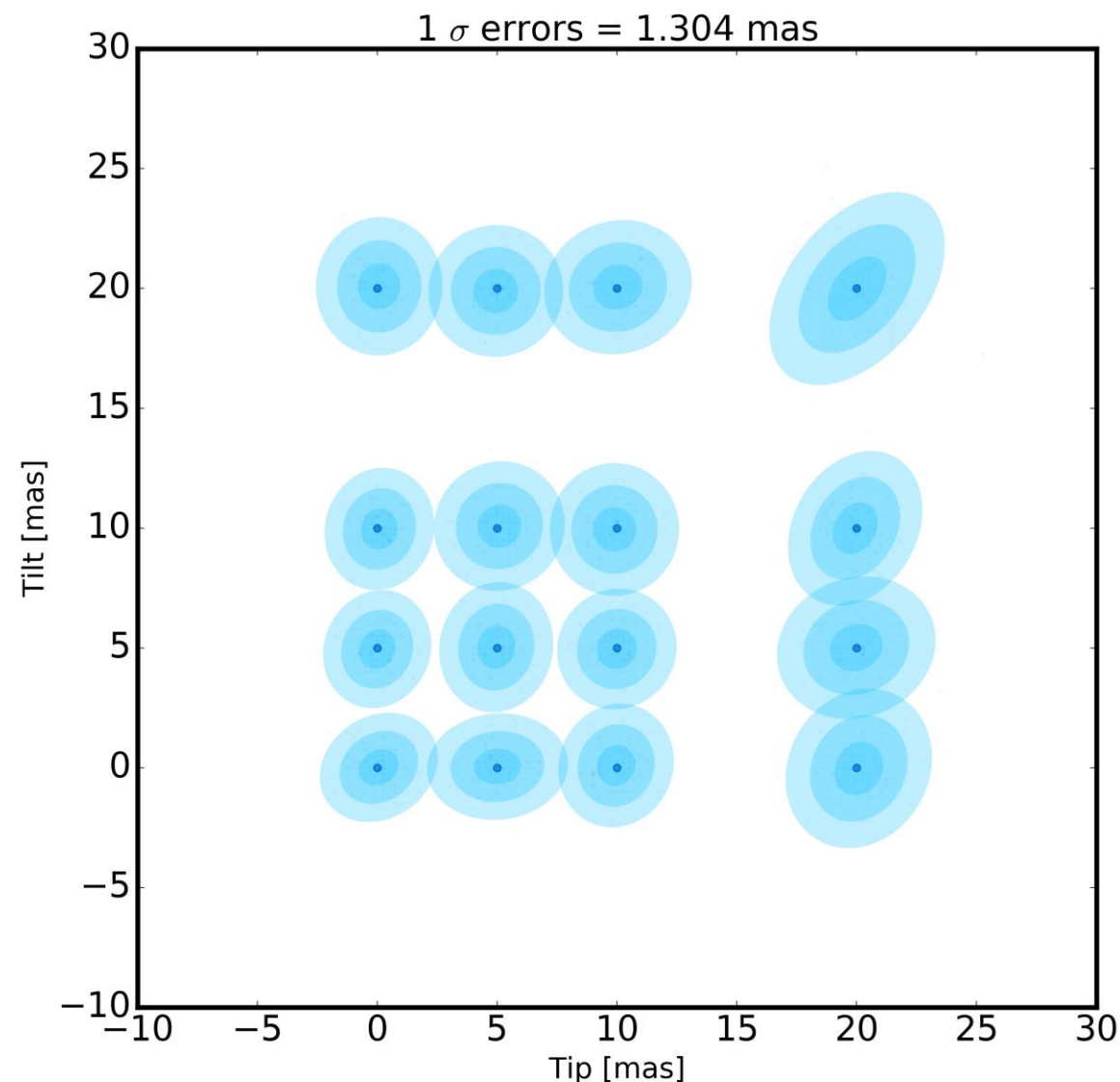
- Methodology: add two noisy camera frames, laser and star, then subtract a model of the shear signal. (this quantifies *photon-limited stellar noise*)
- solve using a matched filter on **only** the laser frames
- **0.01 s exposure time**
 - 5 e- read noise
- **3rd magnitude star**
- **Random shear signal inserted at each iteration**
- **Recovery!**



- Methodology: add two noisy camera frames, laser and star, then subtract a model of the shear signal accurate to $\sim 5\text{cm}$. solve using a matched filter on **only** the laser frames
- **0.01 s exposure time**
 - 5 e- read noise
- **3rd magnitude star**
- **Random shear signal inserted at each iteration**
- **Partial recovery, modest loss of sensitivity compared to perfect knowledge**



- Methodology: add two noisy camera frames, laser and star, then subtract a model of the shear signal accurate to $\sim 5\text{cm}$. solve using a matched filter on **only** the laser frames
- **0.01 s exposure time**
 - 5 e- read noise
- **3rd magnitude star**
- **Random shear signal inserted at each iteration**
- **Partial recovery, modest loss of sensitivity compared to perfect knowledge**
- **60mW laser—big boost**



- Methodology: add two noisy camera frames, laser and star, then subtract a model of the shear signal accurate to $\sim 5\text{cm}$. solve using a matched filter on **only** the laser frames
- **0.01 s exposure time**
 - 5 e- read noise
- **1st magnitude star**
- **Random shear signal inserted at each iteration**
- **Partial recovery, modest loss of sensitivity compared to perfect knowledge**
- **60mW laser—big boost**

